An Integrated Recursive Framework for Arbitrarily Multiscale and Multi-fidelity Modeling

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Multi-Scale Modeling III
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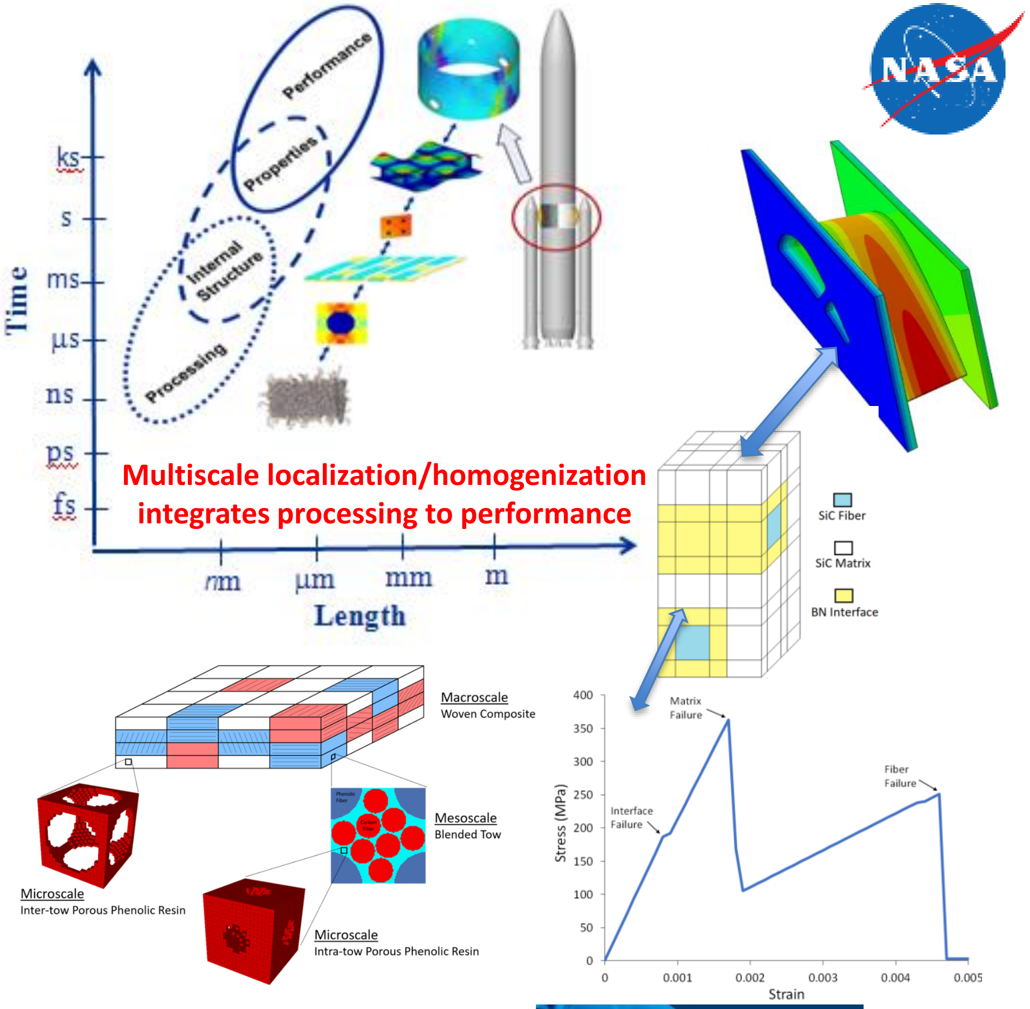
NASA Multiscale Analysis Tool (NASMAT)

- A framework designed to support massively multiscale modeling (M3) on high-performance computing (HPC) systems
  - Solves real, large-scale, non-linear, thermo-mechanical problems

- Modular design to support “plug-and-play” capabilities
  - Operational components categorized into NASMAT procedures
    - Each procedure has access to a library of modules

- Developed for enhanced interoperability
  - Integrates with 3rd party structural analysis codes (e.g., FEA)
  - Arbitrary number of length scales
  - Arbitrary micromechanics theories (including user-defined)
  - Library constitutive laws/damage models (including user-defined)
  - Data output in HDF5 file format

- Ideal for “design with” or “design of” the material
  - Enables Integrated Computational Materials Engineering (ICME)
  - Developed to support NASA Vision 2040

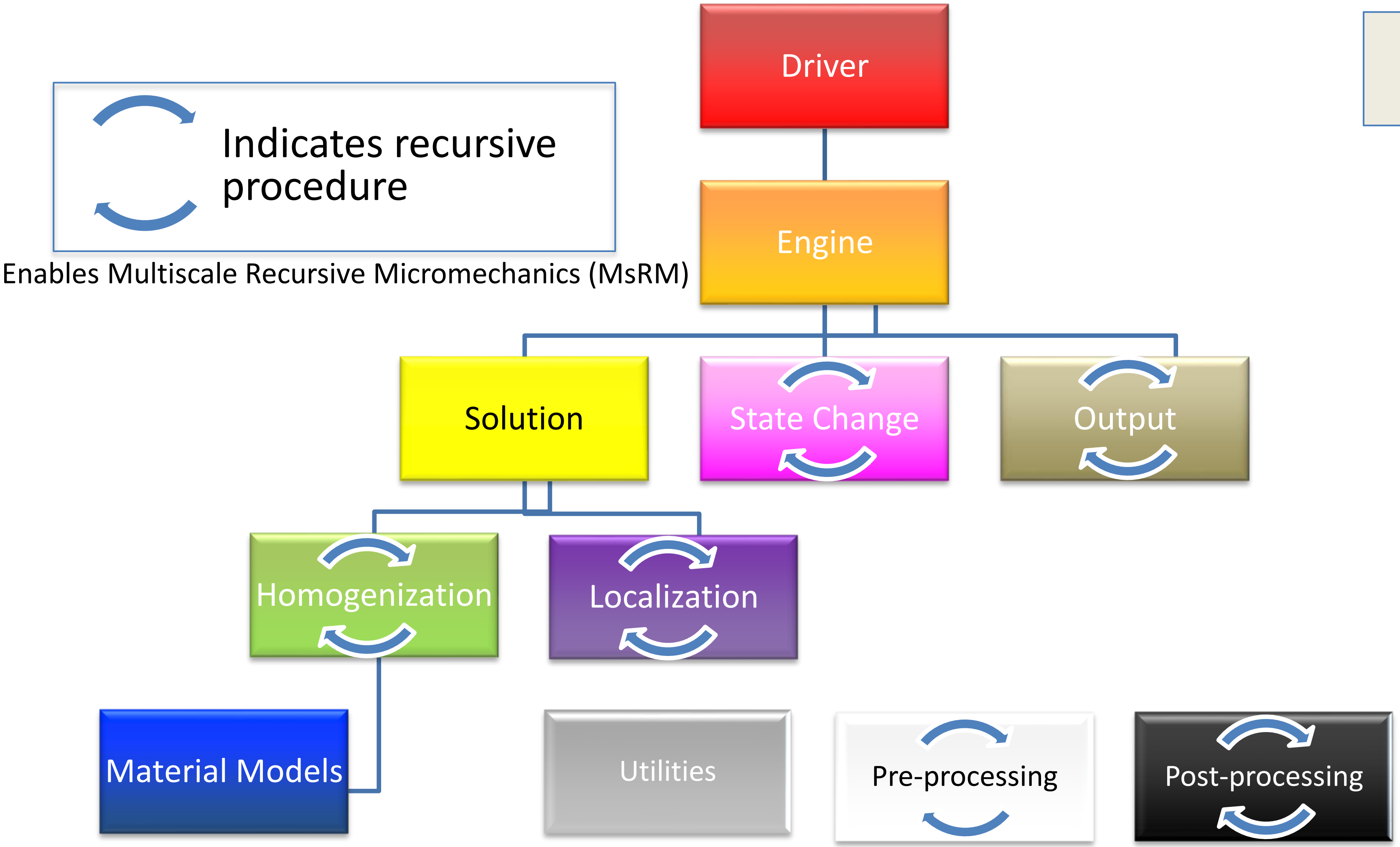


Outline

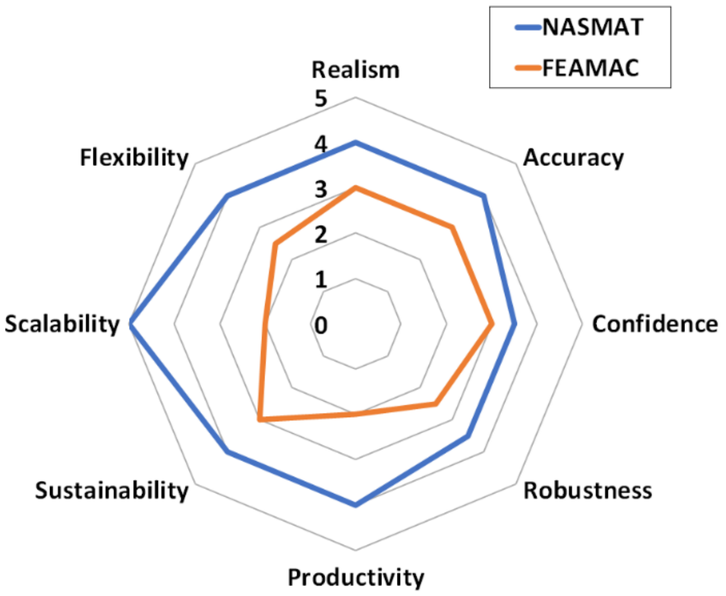
- NASMAT hierarchy
- Multiscale recursive micromechanics (MsRM) framework
- Examples:
  - Progressive failure of 3D woven composites
  - Thermoplastics (PEEK)
  - Multiphysics
  - Dry fabrics
  - Metals
  - Ceramic matrix composite (CMC) turbine vane
- Scaling on high performance computing (HPC) systems
- Development of machine learning (ML) surrogate
- TTT NRAs supporting Vision 2040
- Future of NASMAT

NASMAT
NASA Multiscale Analysis Tool

Version 3.1 – 3/31/22 Public Release
Contact: nasmat@lists.nasa.gov

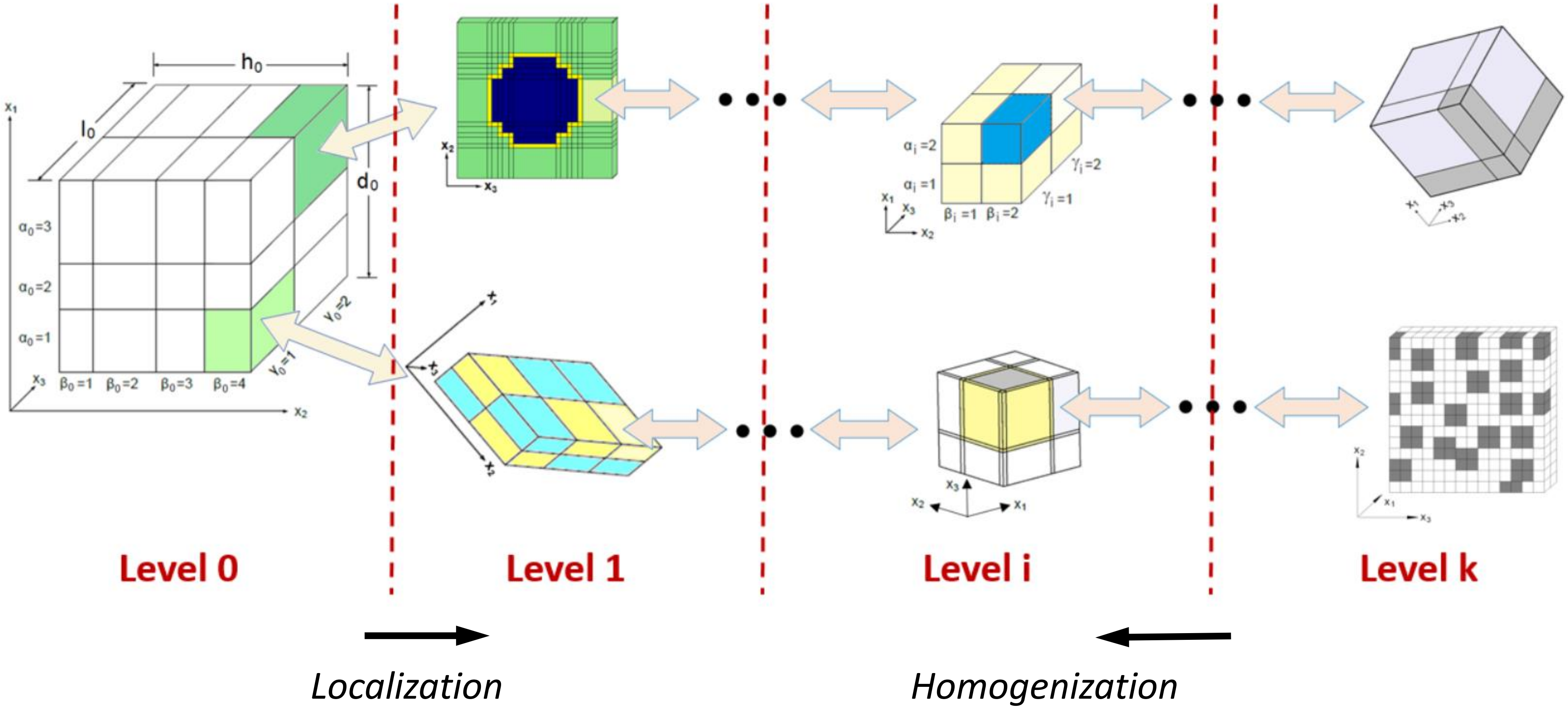


Improvements over legacy multiscale software (FEAMAC)



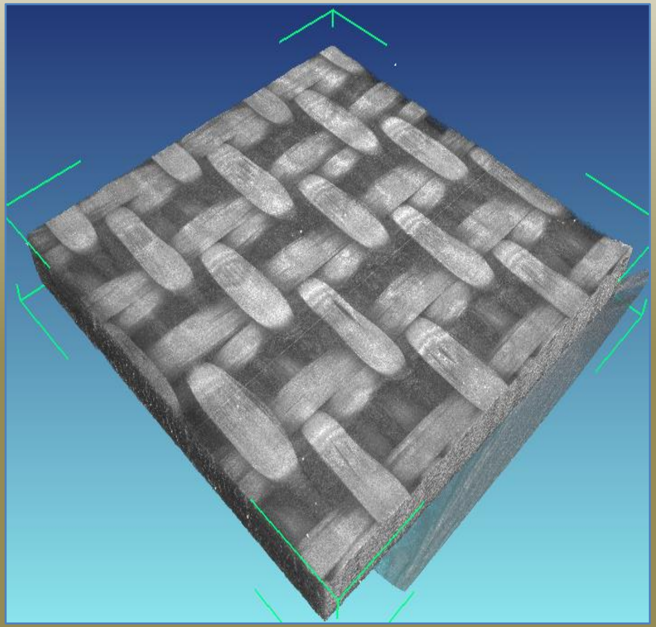
Multiscale Recursive Micromechanics (MsRM)

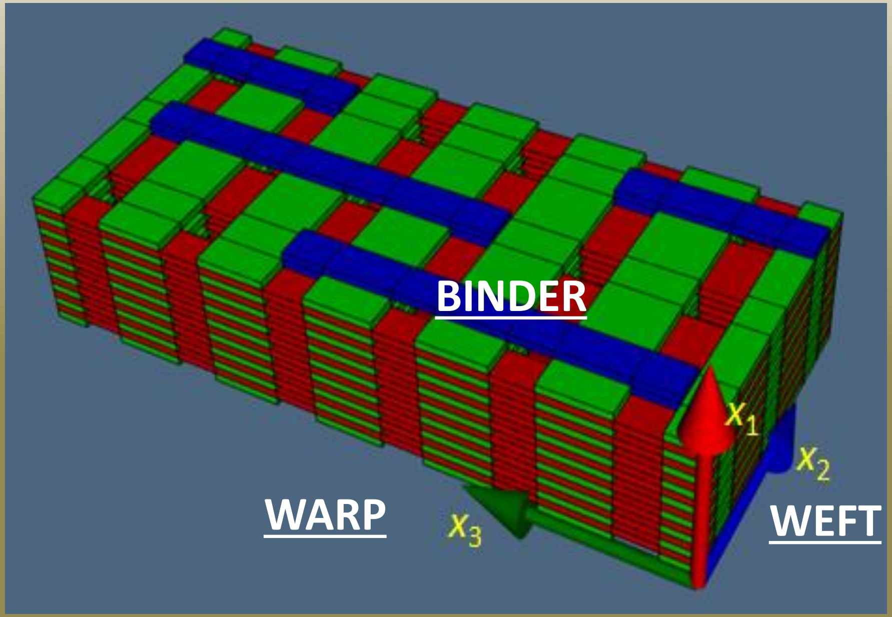
- Efficient, semi-analytical micromechanics theories
- Call each other (or themselves, recursively)
- Captures microstructure on any number of scales
- No limit on depth of scales



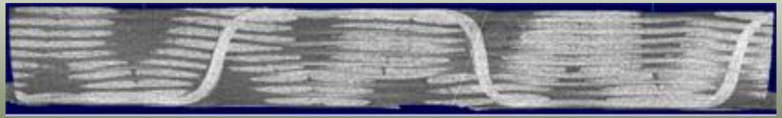
Development of 3D Woven Repeating Unit Cell (RUC)

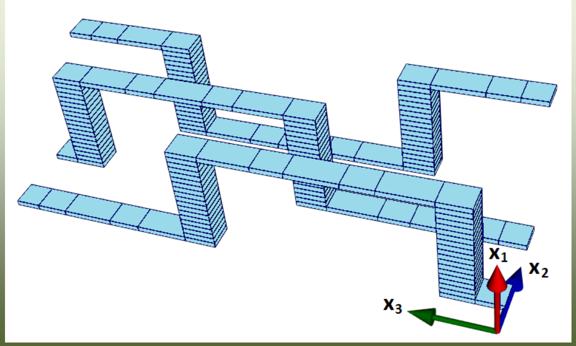
Idealization of Tow Paths from X-Ray CT



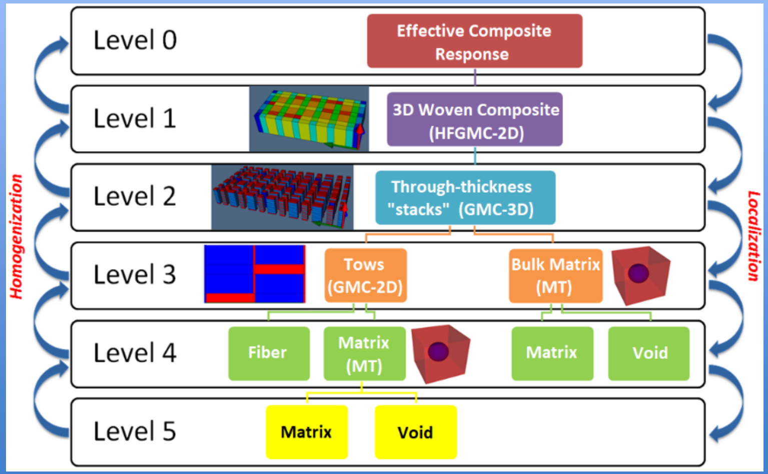


Through-thickness Binder Tow



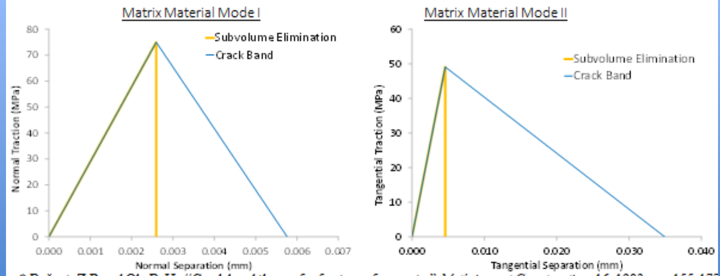


NASMAT MsRM Hierarchy



Damage Modeling

- Subvolume Elimination: simple, brittle, uncoupled modes, no length scale
- Crack Band*: gradual softening, mixed-mode, length scale ties separation/strain



* Bažant, Z.P. and Oh, B. H., "Crack band theory for fracture of concrete," *Matériaux et Construction*, 16, 1983, pp. 155-177

Normal Strength (MPa)	75.0
Shear Strength (MPa)	49.1
G_{IC} (N-mm/mm)	0.216
G_{IIC} (N-mm/mm)	0.857

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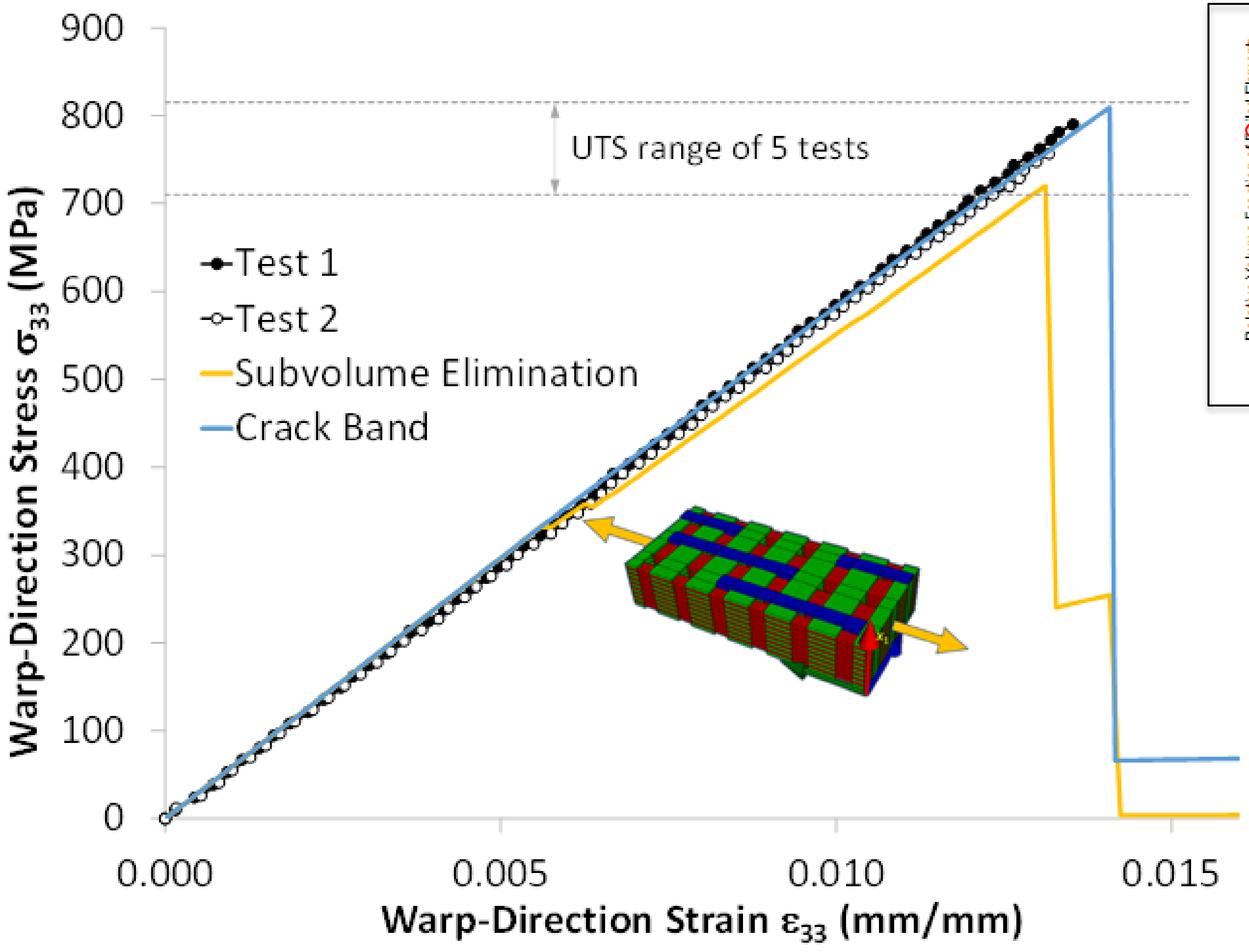
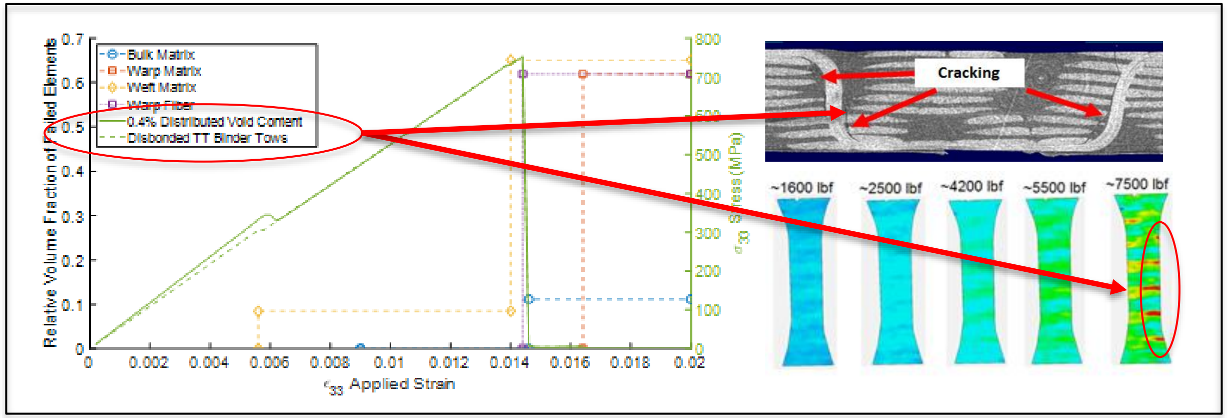
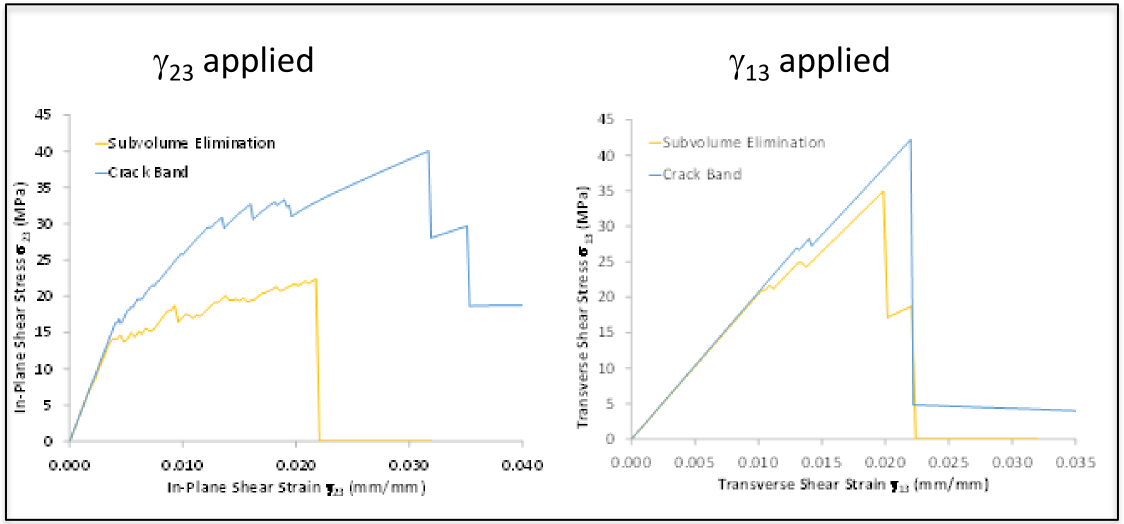
Failure Prediction of 3D Woven Composite



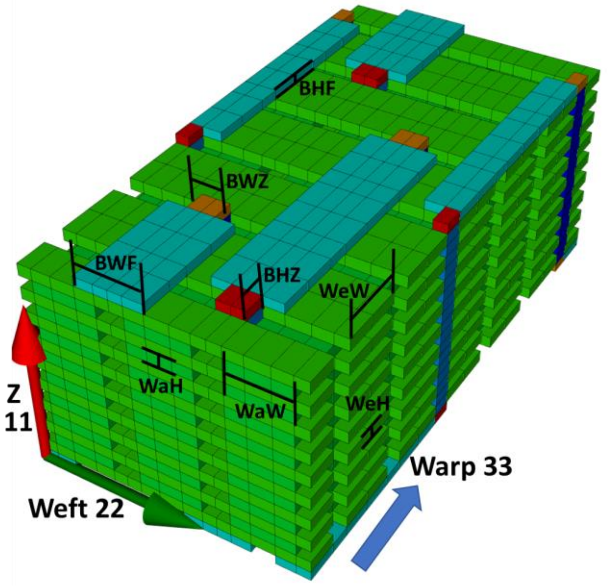


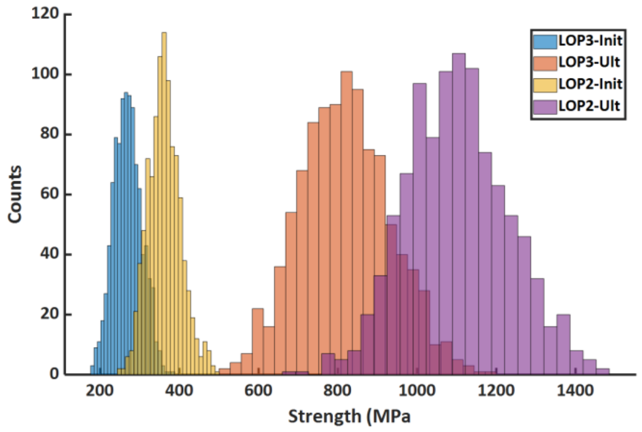


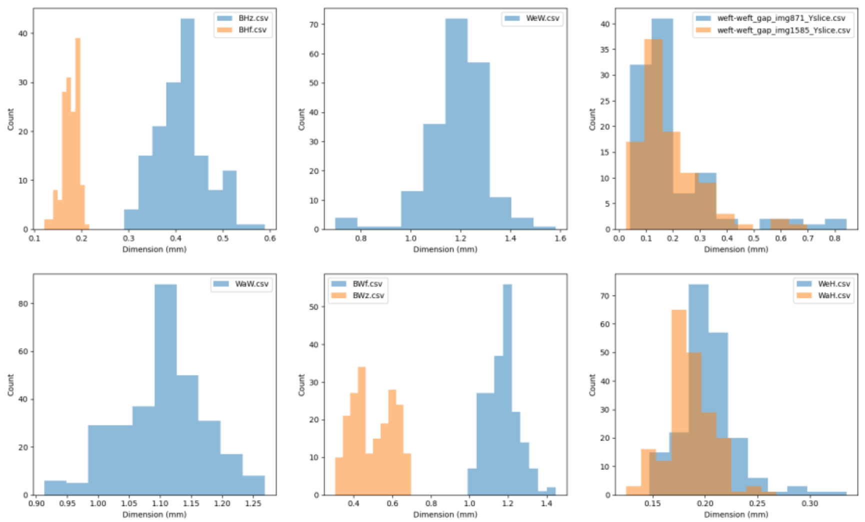
- Warp-direction strength predicted
- Use of quasi-brittle damage model improved overall prediction of stress-strain curve
- Failure mode predicted – disbonding of binder tows
- Crack band model results in more shear nonlinearity
- Runtimes: Subcell elimination ~ 30 sec., crack band ~ 15 min.

Sensitivity Analysis of 3D Woven Composites

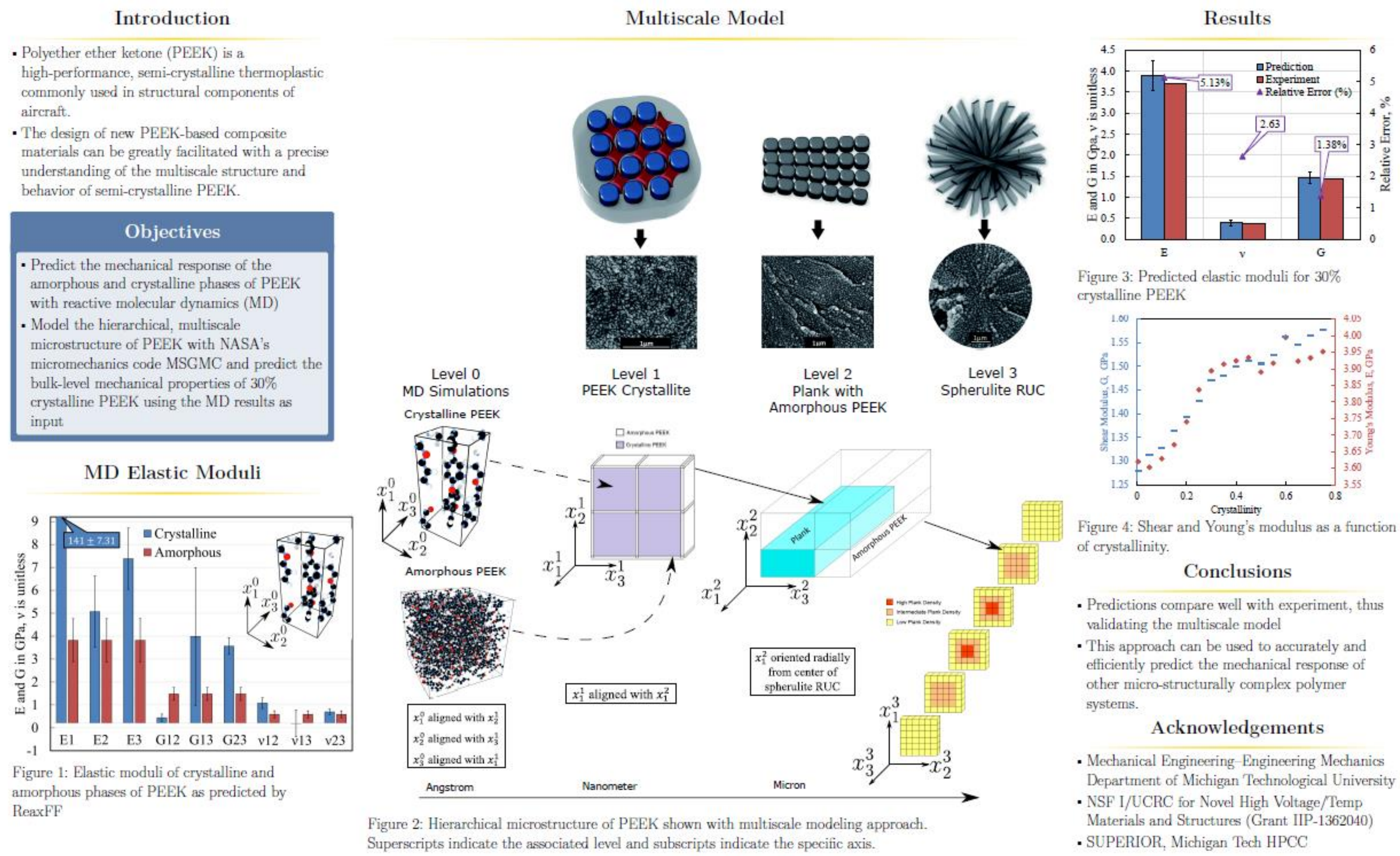
- Ability to capture relevant physics at multiple length scales
- Rapid analysis capability (~sec-min, single CPU) compared to state of the art (~hrs, many CPUs)
- NASMAT successfully coupled to Sandia’s Dakota software
- Ongoing work on sensitivity analysis, and uncertainty quantification







MsRM of Semicrystalline Thermoplastics



Introduction

- Polyether ether ketone (PEEK) is a high-performance, semi-crystalline thermoplastic commonly used in structural components of aircraft.
- The design of new PEEK-based composite materials can be greatly facilitated with a precise understanding of the multiscale structure and behavior of semi-crystalline PEEK.

Objectives

- Predict the mechanical response of the amorphous and crystalline phases of PEEK with reactive molecular dynamics (MD)
- Model the hierarchical, multiscale microstructure of PEEK with NASA's micromechanics code MSGMC and predict the bulk-level mechanical properties of 30% crystalline PEEK using the MD results as input

MD Elastic Moduli

Figure 1: Elastic moduli of crystalline and amorphous phases of PEEK as predicted by ReaxFF

Multiscale Model

Figure 2: Hierarchical microstructure of PEEK shown with multiscale modeling approach. Superscripts indicate the associated level and subscripts indicate the specific axis.

Results

Figure 3: Predicted elastic moduli for 30% crystalline PEEK

Figure 4: Shear and Young's modulus as a function of crystallinity.

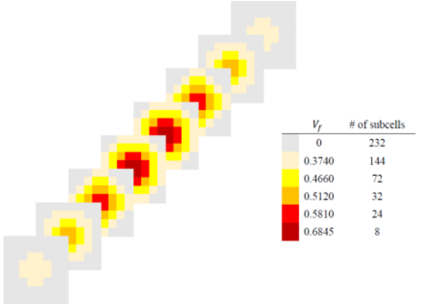
Conclusions

- Predictions compare well with experiment, thus validating the multiscale model
- This approach can be used to accurately and efficiently predict the mechanical response of other micro-structurally complex polymer systems.

Acknowledgements

- Mechanical Engineering–Engineering Mechanics Department of Michigan Technological University
- NSF I/UCRC for Novel High Voltage/Temp Materials and Structures (Grant IIP-1362040)
- SUPERIOR, Michigan Tech HPCC

- Prelim. Work – collaboration with MTU
- RUC extended to HFGMC, spherical
  - Completed by UMass Lowell intern



- Model will be extended to incorporate spherulite growth

Physics Governed by Vector Constitutive Laws

Heat conduction (Fourier's Law)	$\mathbf{q} = -\boldsymbol{\kappa} \nabla T$	$\mathbf{q} = \textit{heat flux vector}$ $\boldsymbol{\kappa} = \textit{2nd order thermal conductivity tensor}$ $T = \textit{temperature}$	
Electrical conduction	$\mathbf{J} = -\boldsymbol{\sigma} \nabla \phi$	$\mathbf{J} = \textit{electic current density vector}$ $\boldsymbol{\sigma} = \textit{2nd order electric conductivity tensor}$ $\phi = \textit{electical potential}$	$\textit{Electric field}:$ $\mathbf{E} = -\nabla \phi$
Diffusion (Fick's Law)	$\mathbf{j} = -\mathbf{d} \nabla C$	$\mathbf{j} = \textit{permeant flux vector}$ $\mathbf{d} = \textit{2nd order diffusivity tensor}$ $C = \textit{concentration}$	
Magnetic permeability	$\mathbf{B} = -\boldsymbol{\mu} \nabla \xi$	$\mathbf{J} = \textit{magnetic flux density vector}$ $\boldsymbol{\sigma} = \textit{2nd order magnetic permeability tensor}$ $\phi = \textit{magnetic potential}$	$\textit{Magnetic field}:$ $\mathbf{H} = -\nabla \xi$
Electrical permittivity	$\mathbf{D} = -\boldsymbol{\varepsilon} \nabla \phi$	$\mathbf{D} = \textit{electric displacement vector}$ $\boldsymbol{\varepsilon} = \textit{2nd order electric permittivity tensor}$ $\phi = \textit{electric potential}$	$\textit{Electric field}:$ $\mathbf{E} = -\nabla \phi$
In General	$\mathbf{Y} = -\mathbf{Z} \nabla \psi = \mathbf{Z}\,\mathbf{X}$	Governing Equation:	$\nabla \cdot \mathbf{Y} = 0$

High-Fidelity Generalized Method of Cells (HFGMC)

- All of these physics can be handled by same HFGMC formulation
- Predicts:
  - Effective properties (given constituent properties and arrangement)
  - Local fields (given global field loading)

- Second order potential or (temperature, etc.) expansion:

$$\psi^{(\alpha\beta\gamma)} = \bar{X}_j x_j + \theta^{(\alpha\beta\gamma)}_{(000)} + \bar{y}_1^{(\alpha)}\theta^{(\alpha\beta\gamma)}_{(100)} + \bar{y}_2^{(\beta)}\theta^{(\alpha\beta\gamma)}_{(010)} + \bar{y}_3^{(\gamma)}\theta^{(\alpha\beta\gamma)}_{(001)}$$

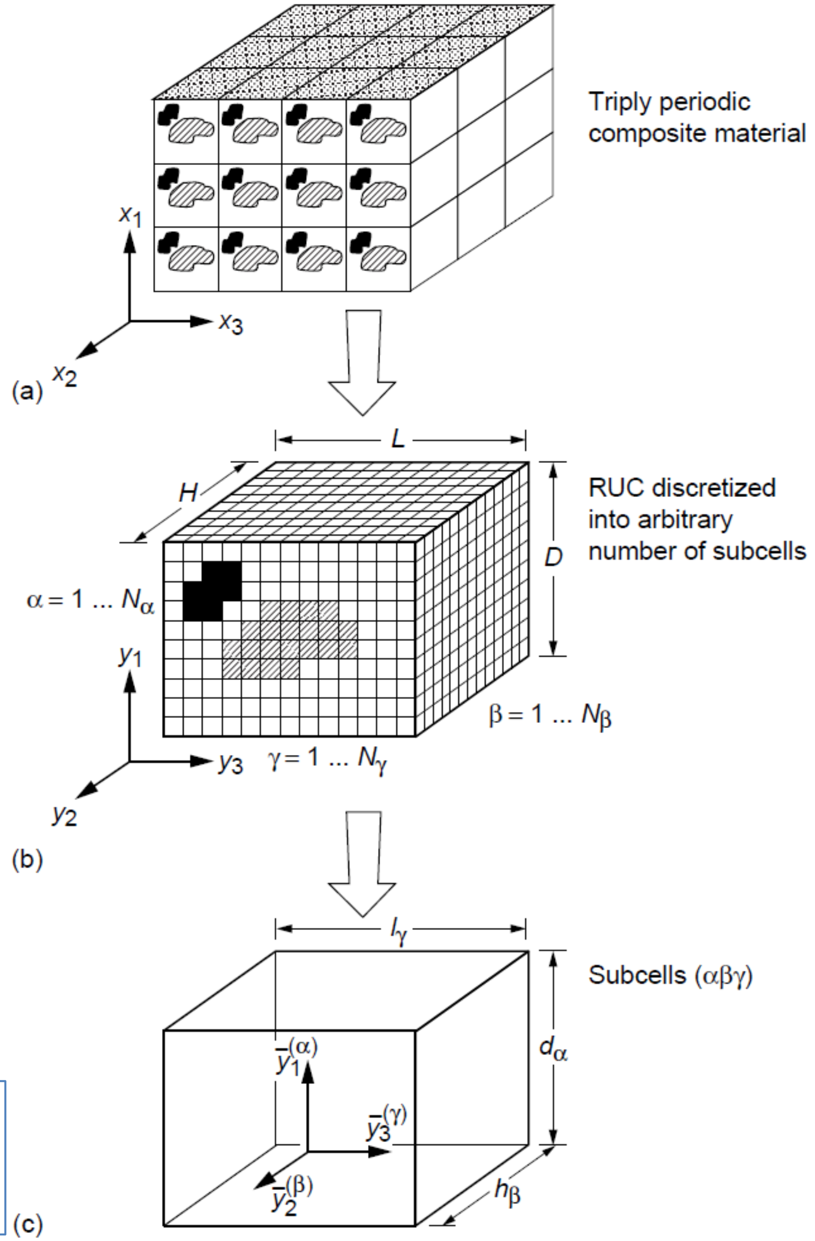
$$+\frac{1}{2}\left(3\bar{y}_1^{(\alpha)2} - \frac{d_\alpha^2}{4}\right)\theta^{(\alpha\beta\gamma)}_{(200)} + \frac{1}{2}\left(3\bar{y}_2^{(\beta)2} - \frac{h_\beta^2}{4}\right)\theta^{(\alpha\beta\gamma)}_{(020)} + \frac{1}{2}\left(3\bar{y}_3^{(\gamma)2} - \frac{l_\gamma^2}{4}\right)\theta^{(\alpha\beta\gamma)}_{(002)}$$

- System of $3N_\alpha N_\beta N_\gamma$ algebraic equations: $\mathbf{K}\,\mathbf{\Omega} = \mathbf{f}$

- Concentration equation: $\boxed{\mathbf{X}^{(\alpha\beta\gamma)} = \mathbf{A}^{(\alpha\beta\gamma)}\,\bar{\mathbf{X}}}$

- Global (effective) constitutive equation: $\bar{\mathbf{Y}} = \mathbf{Z}^*\,\bar{\mathbf{X}}$

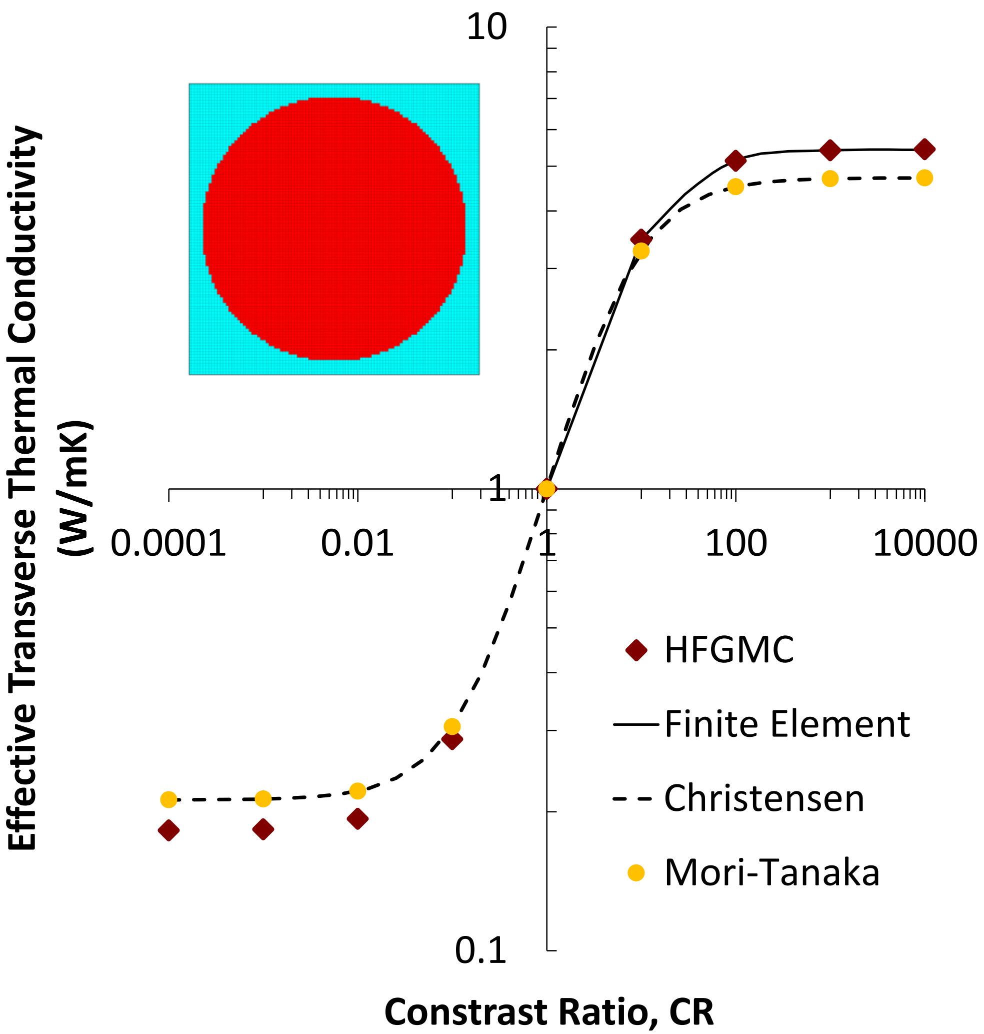
- Where, effective property tensor is: $\boxed{\mathbf{Z}^* = \frac{1}{DHL}\sum_{\alpha=1}^{N_\alpha}\sum_{\beta=1}^{N_\beta}\sum_{\gamma=1}^{N_\gamma} d_\alpha h_\beta l_\gamma\,\mathbf{Z}^{(\alpha\beta\gamma)}\,\mathbf{A}^{(\alpha\beta\gamma)}}$



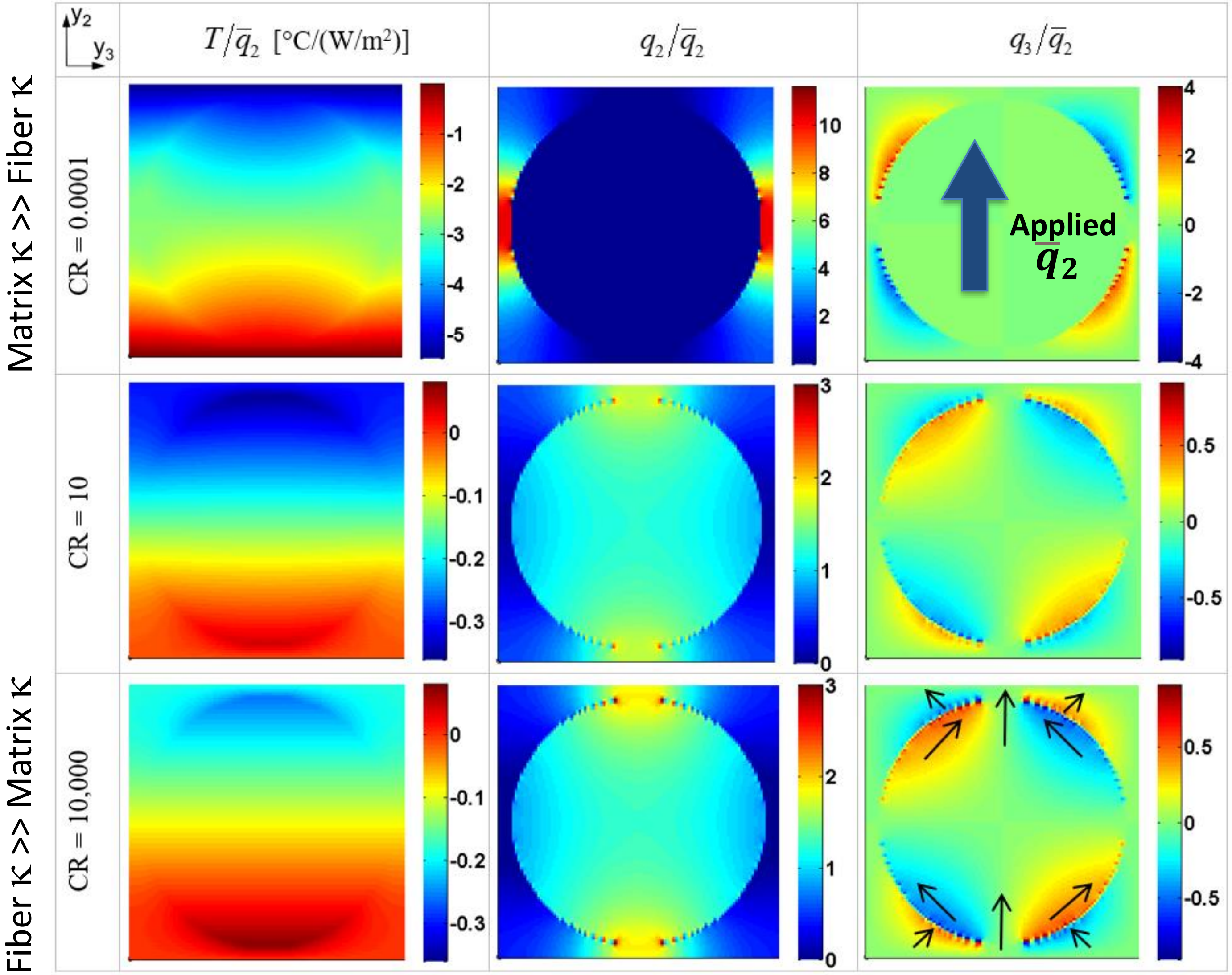
Verification – Thermal Conductivity

- Unidirectional composite with varying fiber/matrix thermal conductivity contrast ratio (CR)

Effective Thermal Conductivity

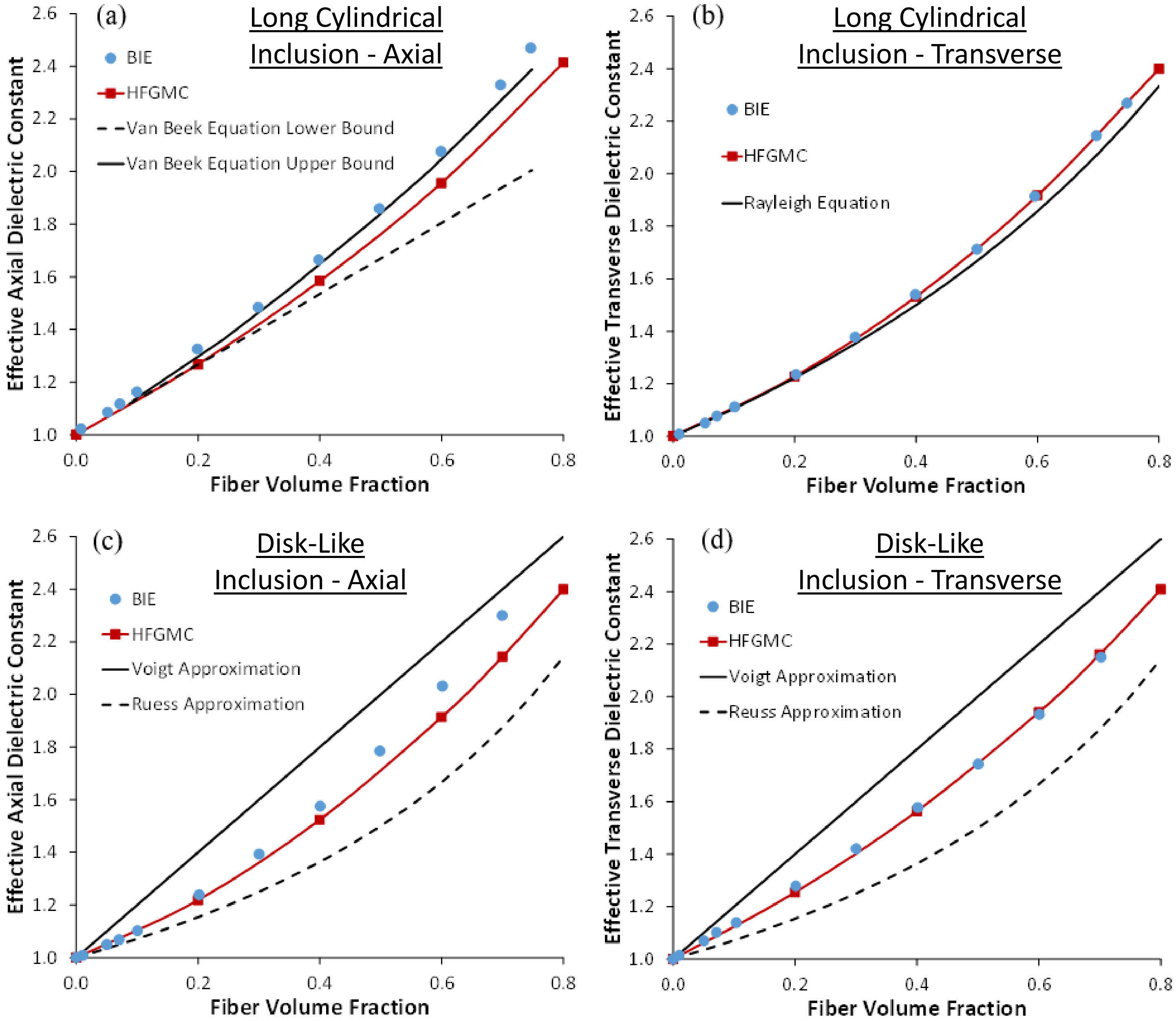


Local Temperature and Heat Flux Fields

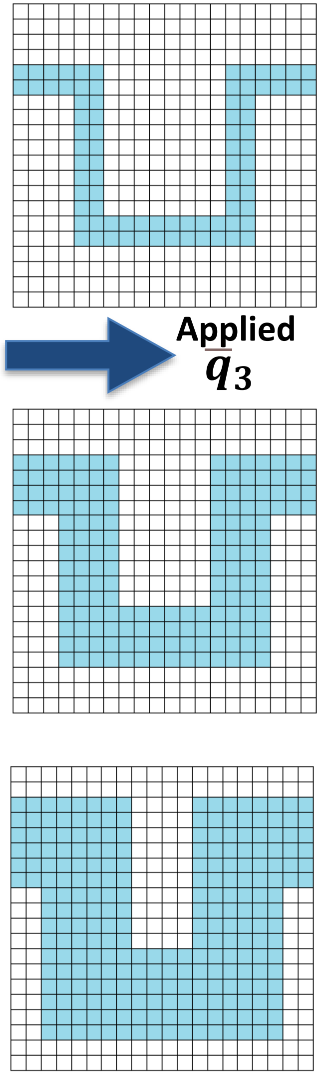


Verification – Electrical Permittivity

- Effective Dielectric Constants:

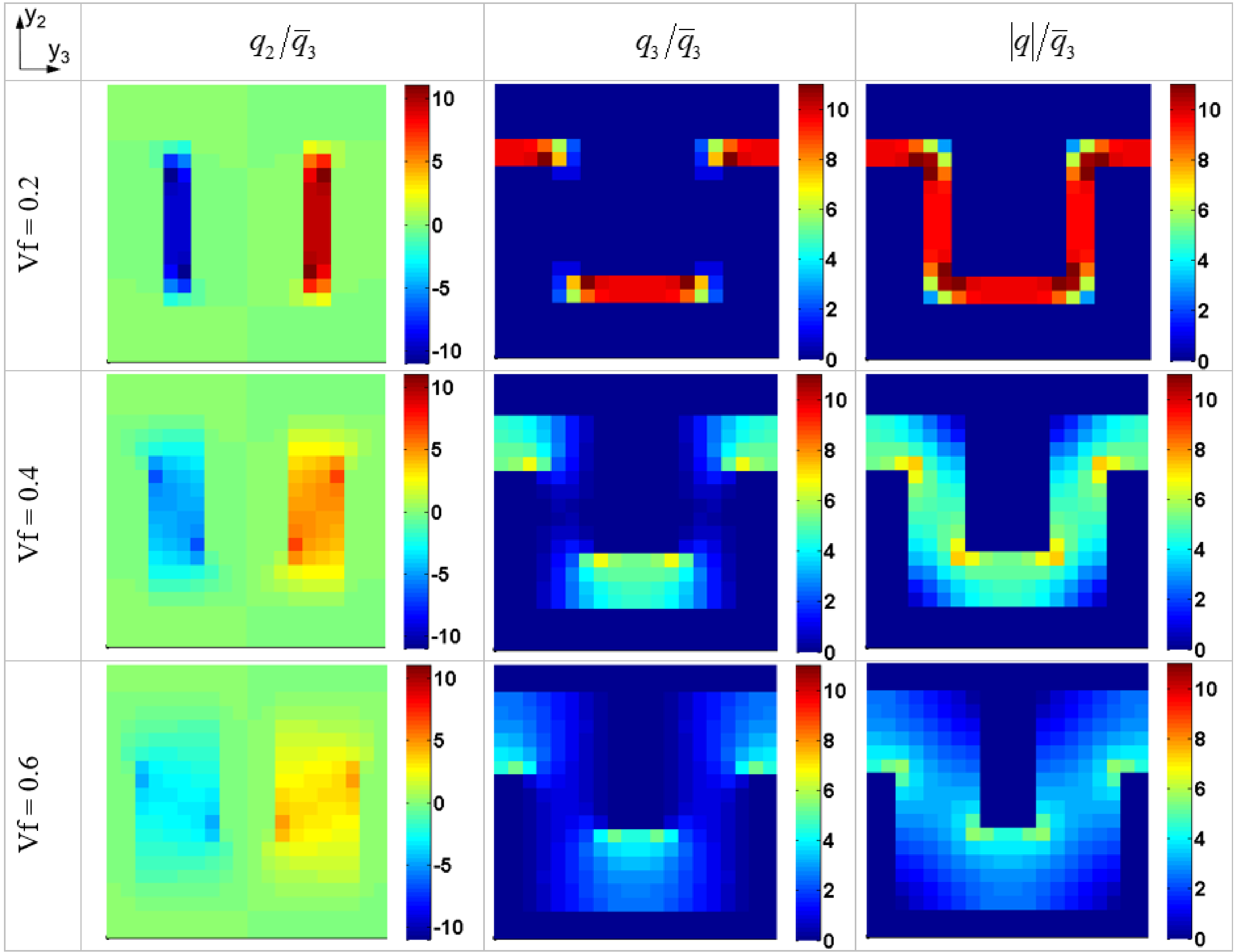


Verification – Ability to Capture Tortuous Flux Path

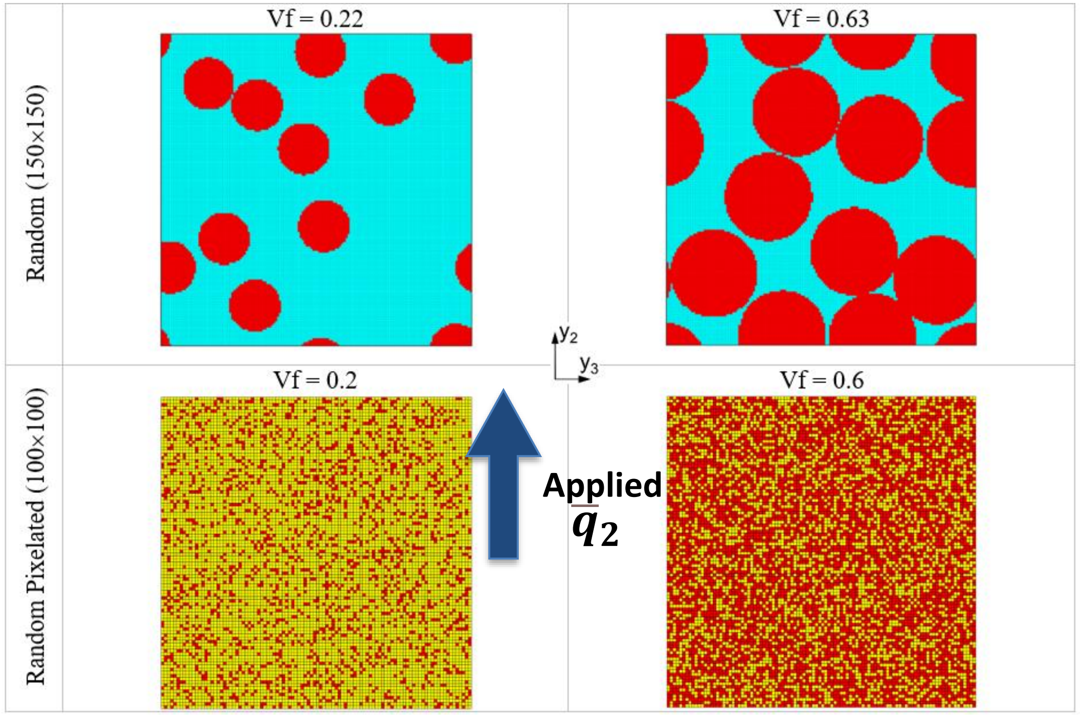


Blue = High κ
White = Low κ

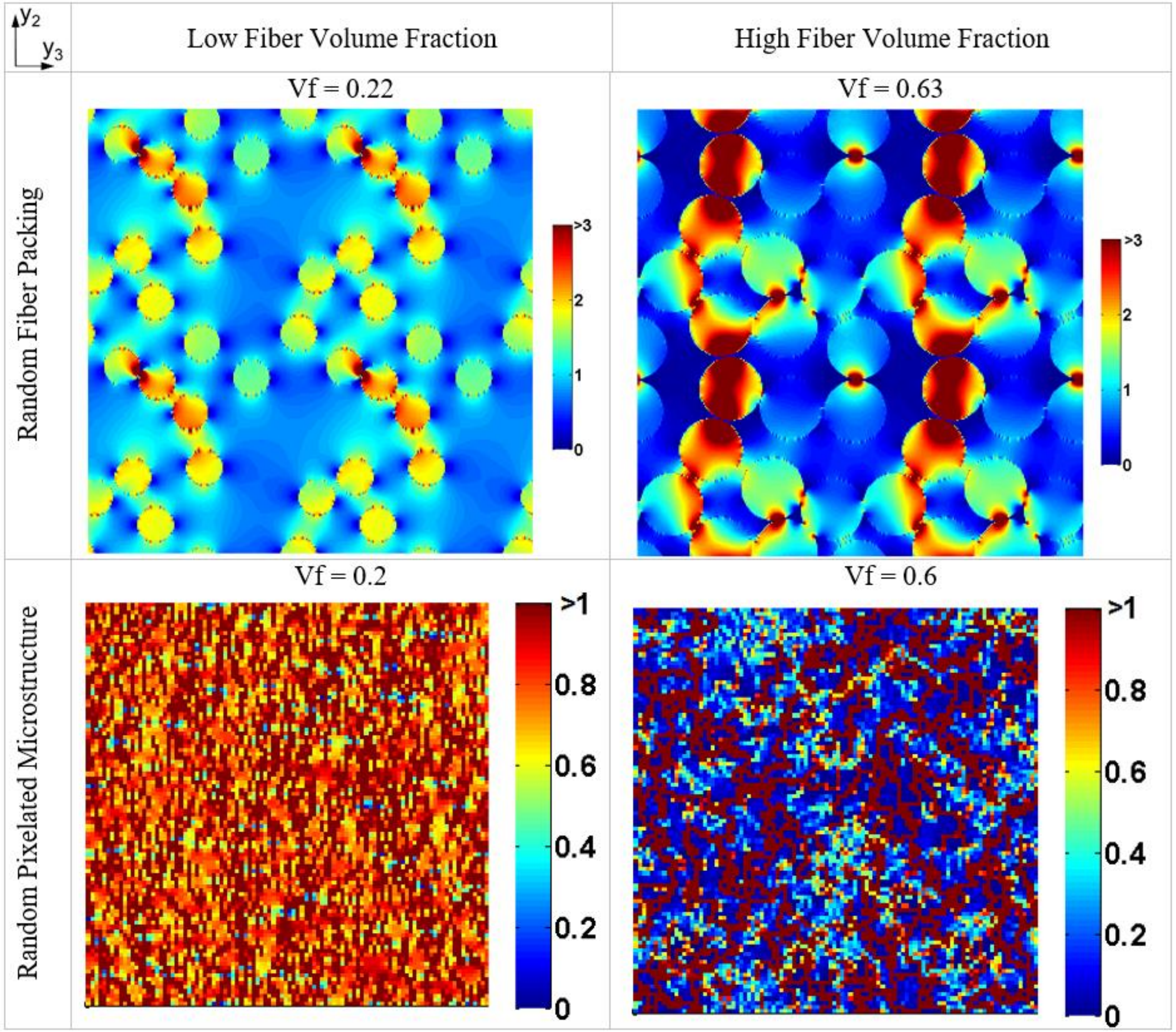
Local Heat Flux Fields



Application to Random Microstructures



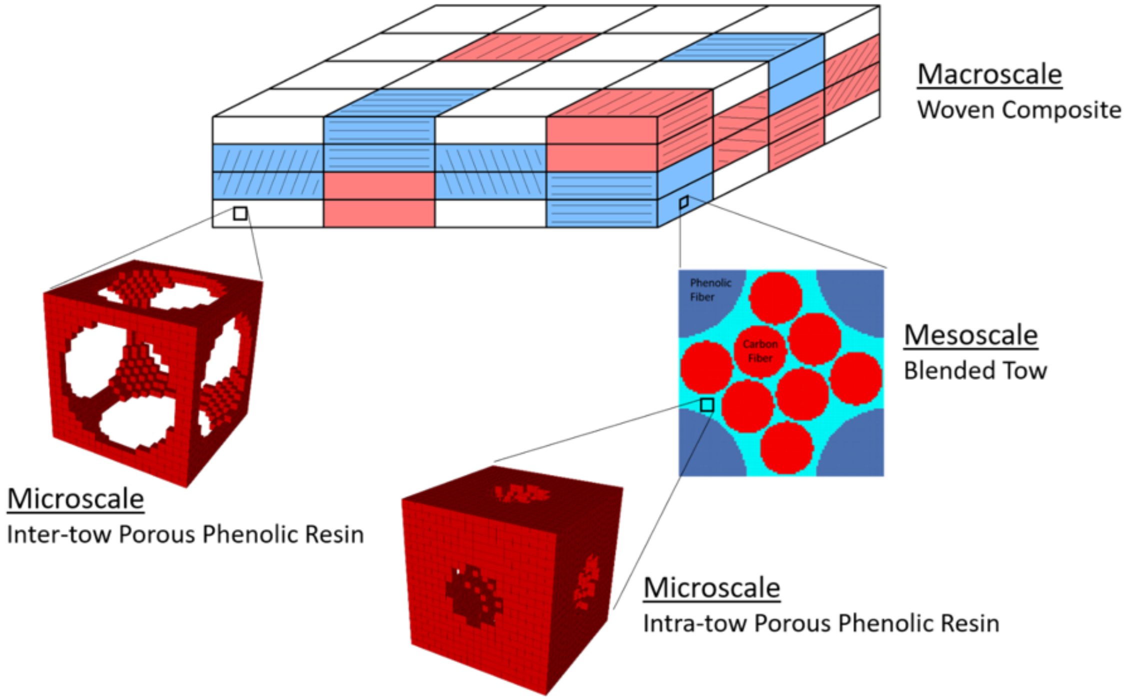
Local Heat Flux Fields



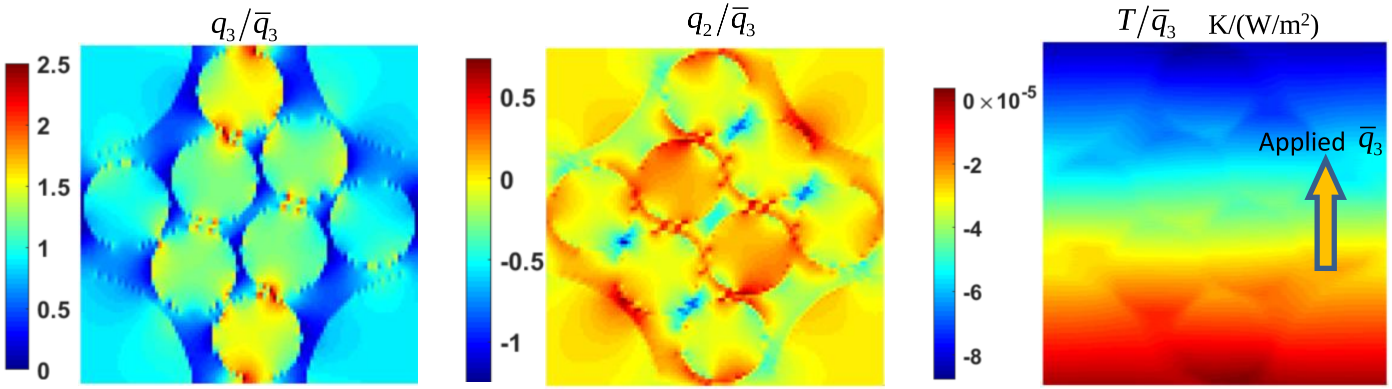
Above "percolation threshold"

Multiscale Thermal Conductivity – C/Phenolic TPS Material

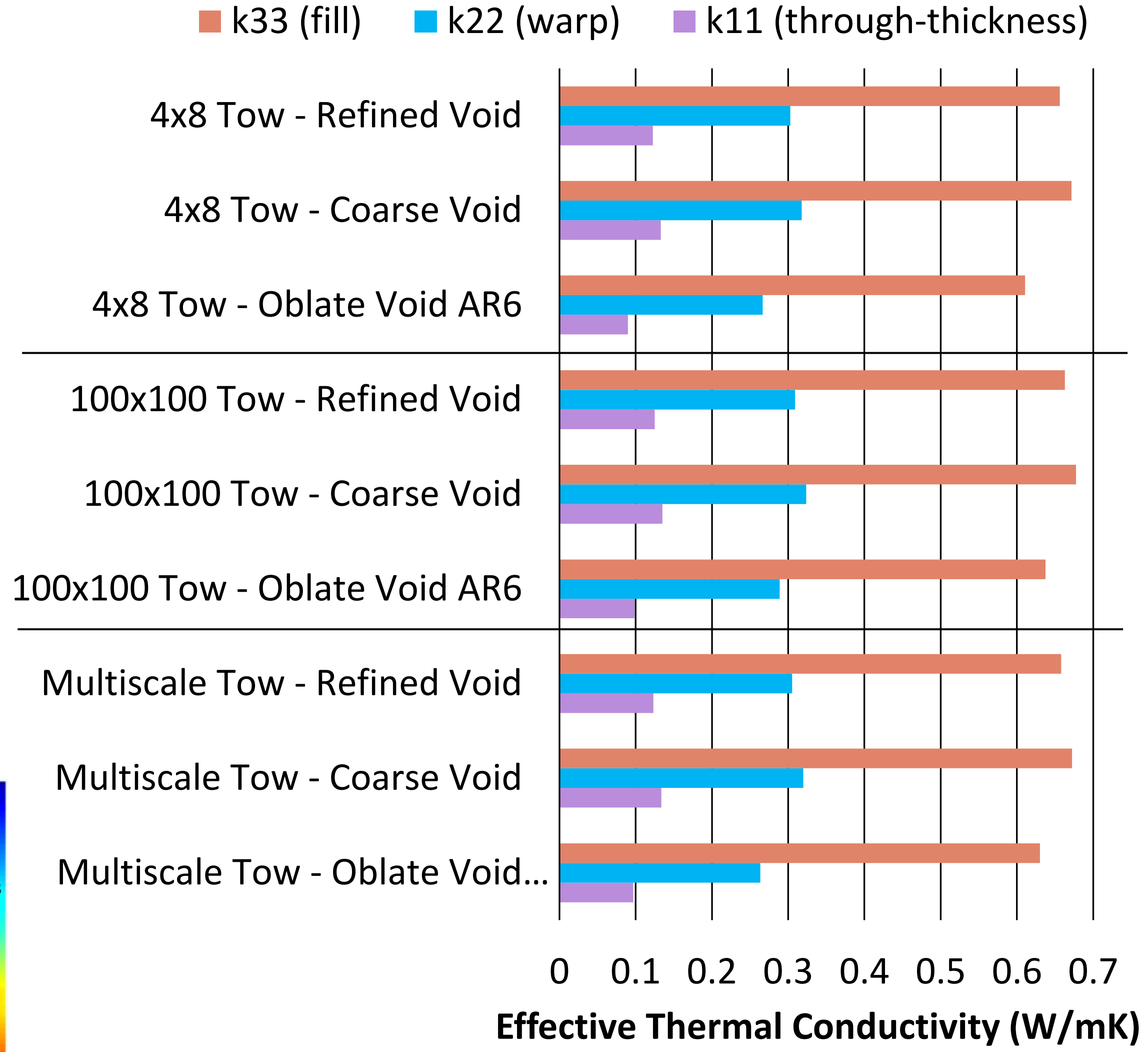
- Three scales (woven composite/tows/voids)



Sample local flux and temperature fields in tow (normalized)

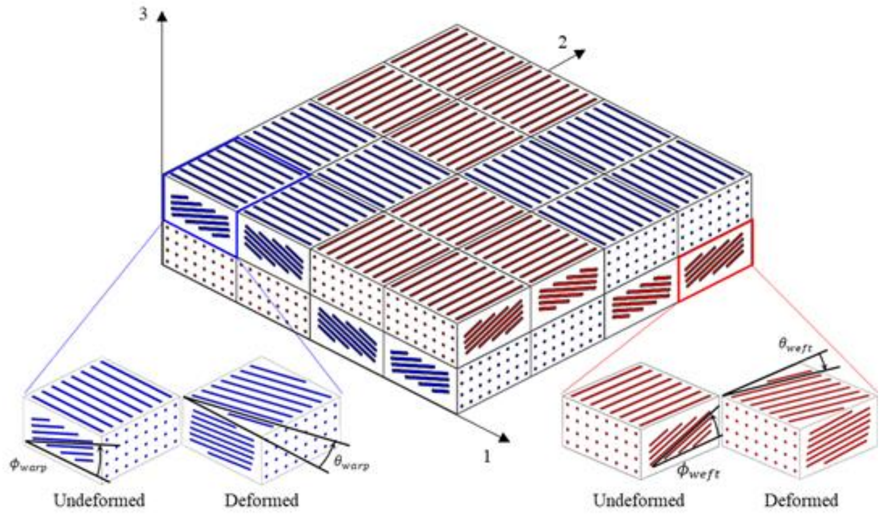


Anisotropic effective thermal conductivity as a function of tow and void representation

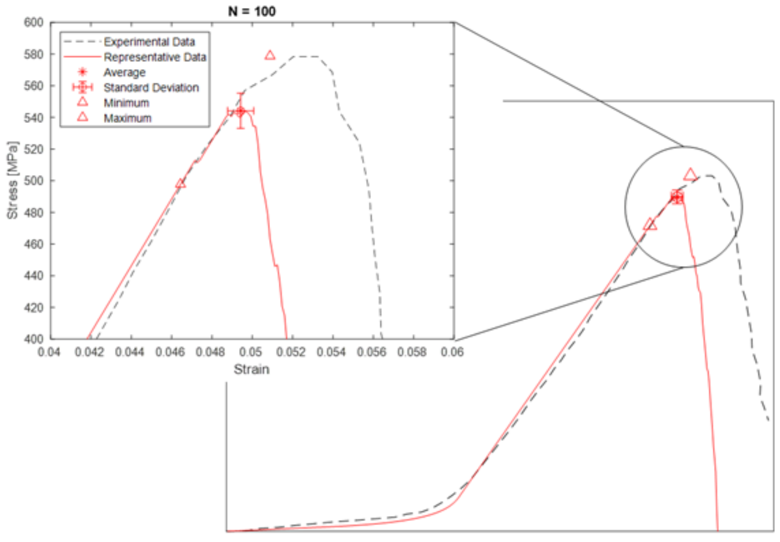


Dry Fabrics for Entry Parachute Applications

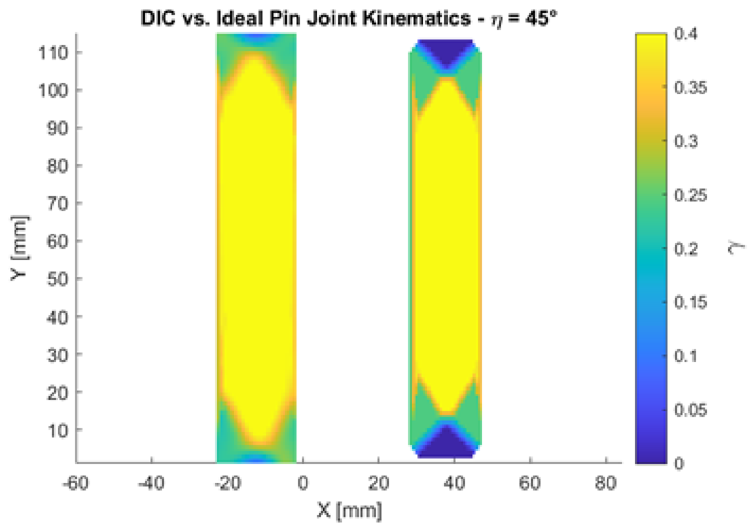
- Simulate dry fabric behavior by allowing the tow orientation in each subcell to change with applied loading
  - ϕ – Crimp or tow undulation angle
  - θ – Relative tow rotation angle
- Failure predicted for both fiber breakage and yarn pullout
  - Fiber breakage accounts for statistical variation observed experimentally
  - Yarn pullout failure criteria developed for macroscale (coupon)
    - Able to capture full field strain development



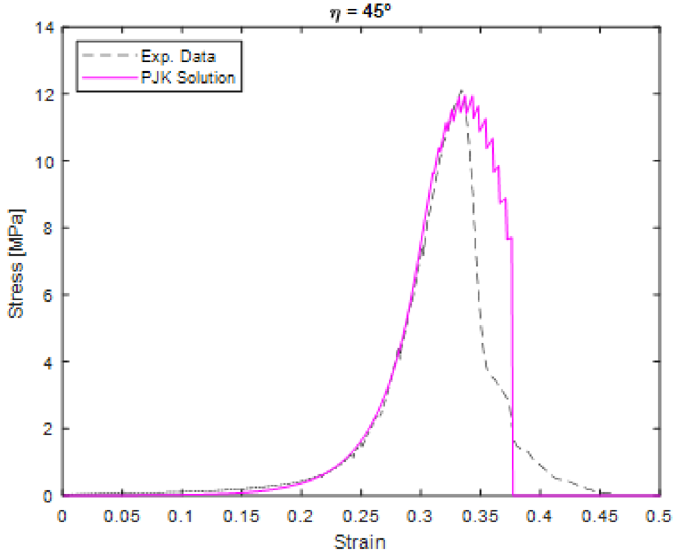
Fabric RUC with defining angles



Warp-Aligned Uniaxial Tension (100 simulations)



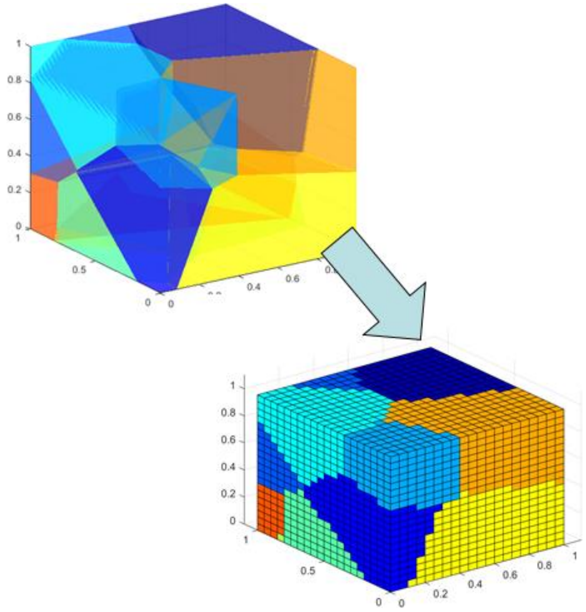
Bias Extension Shear Strain Development



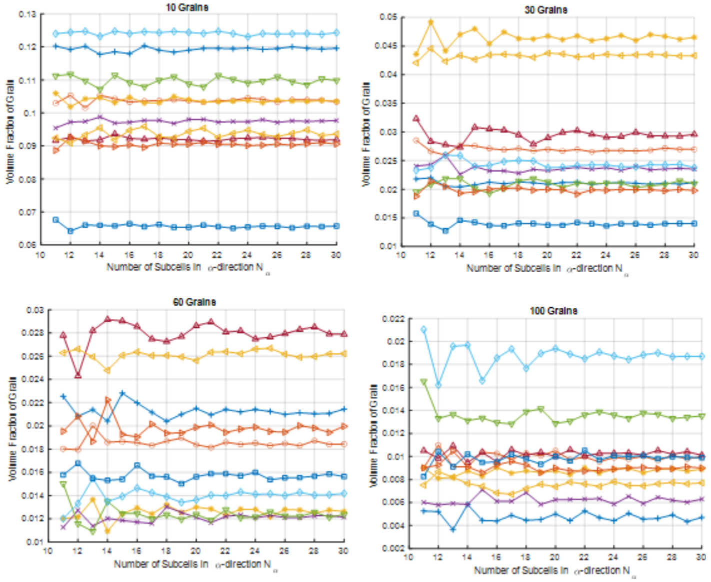
Bias Extension Simulation

MsRM of Polycrystalline Metallics

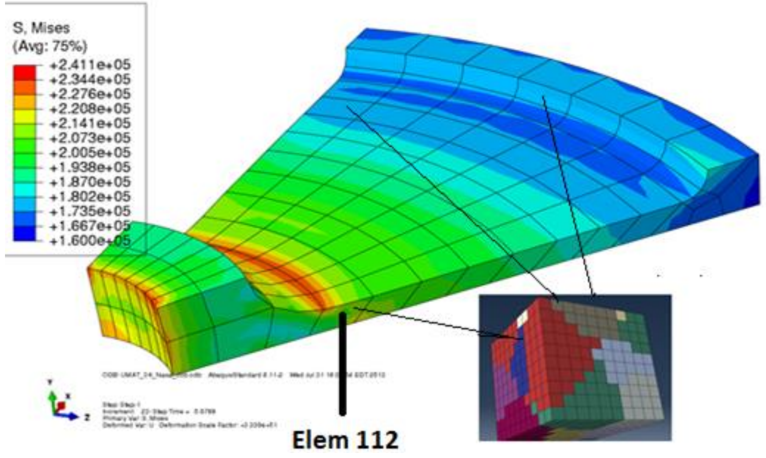
Voxelization of polycrystalline RUC for HF/GMC analysis



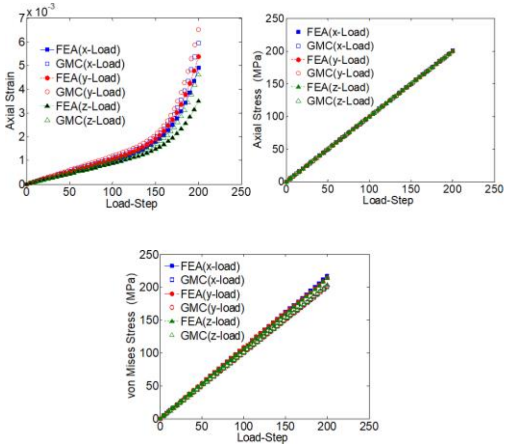
Study on size effect and grid refinement

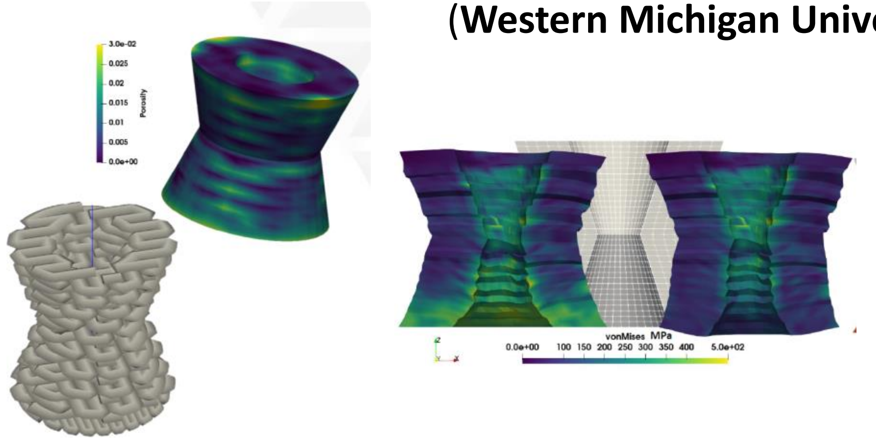


Multiscale Modeling: Supported through NASA SBIR – **ADDITIVE MANUFACTURING INNOVATIONS, LLC; PI: Ajit Achuthan**

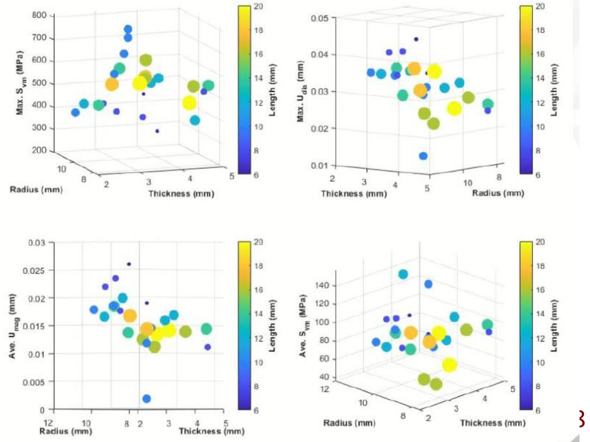


Single-crystal plasticity – collab. with **Achuthan (Clarkson University)**



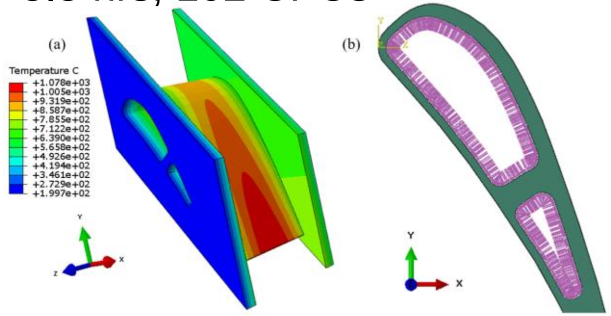


Additive Manufacturing: collab. with **Gustafson (Western Michigan University)**

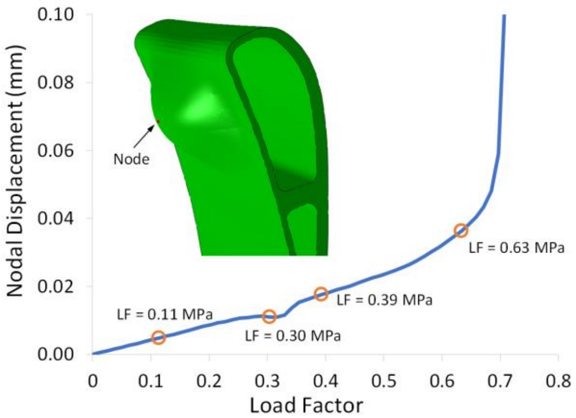


Application to a Realistic Structure

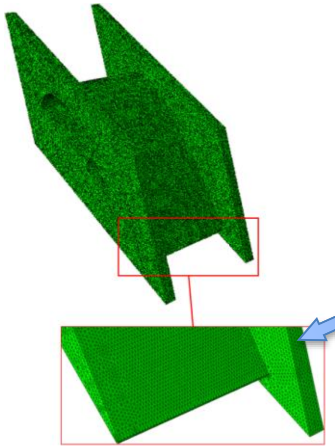
- Multiscale simulation of realistic SiC/SiC CMC turbine vane subjected to thermal and internal pressure loading
  - Fully integrated nonlinear analysis
    - 5.5 hrs, 102 CPUs

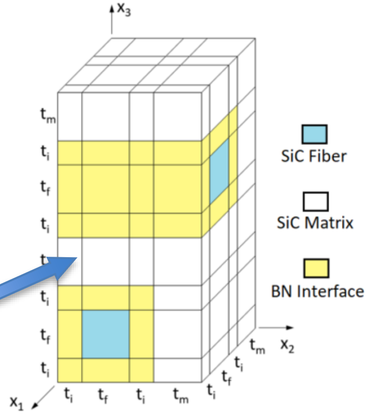


- Nodal displacement monitored as cavity bursts

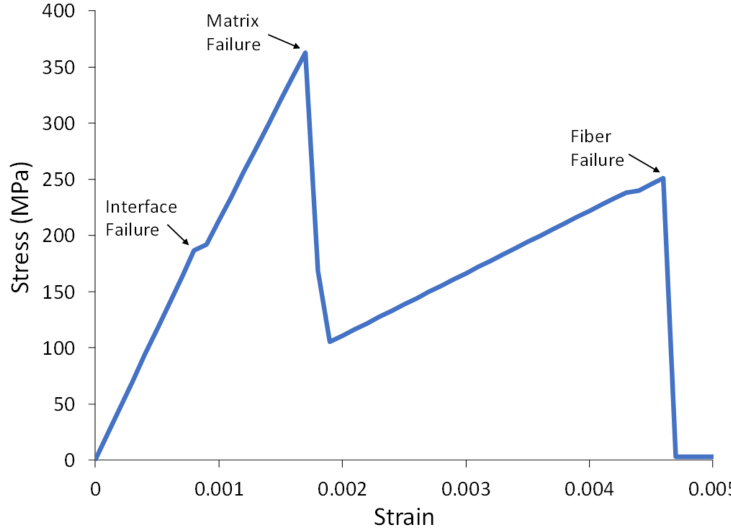


- FE Mesh ~0.5M C3D10 quadratic tets
- GMC3D SiC/SiC CMC RUC
  - 128 subcells

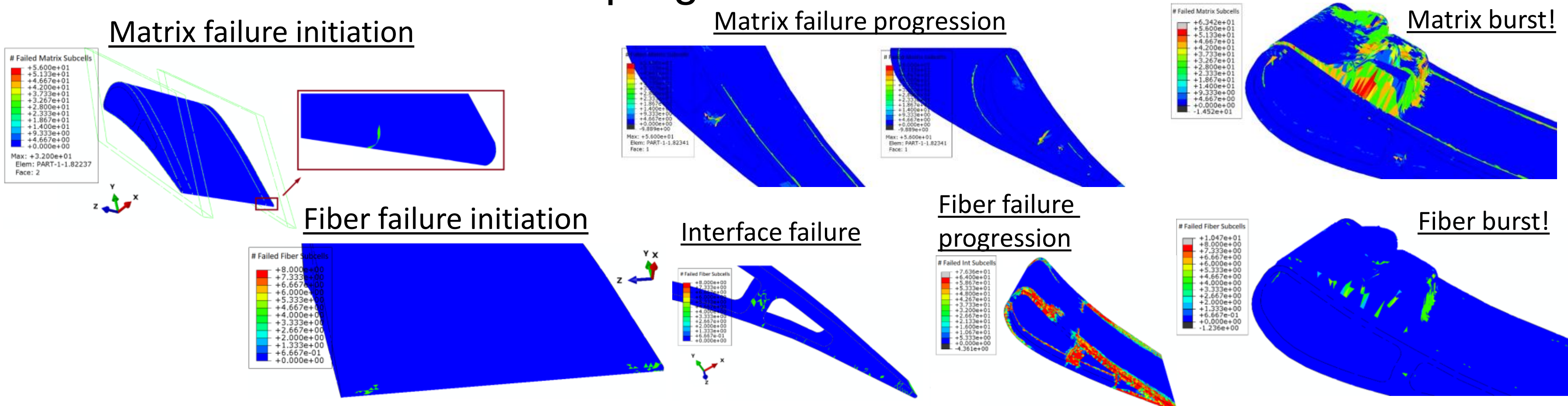




- Failure invoked at the microscale in the constituents



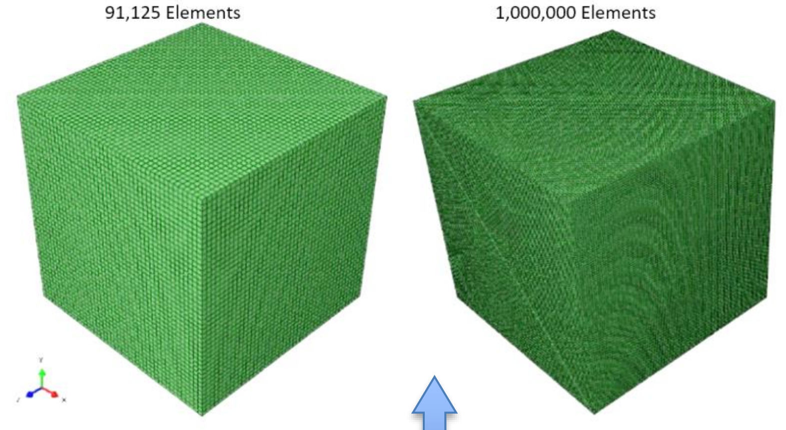
- Failure progression monitored in constituent



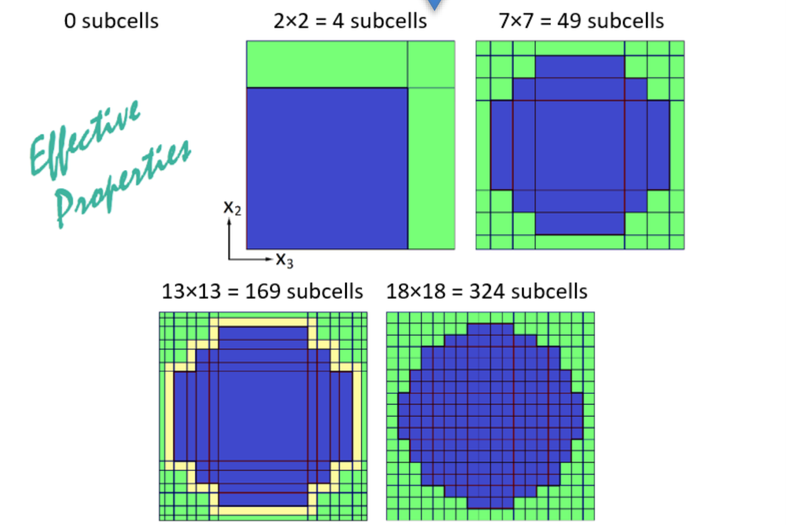
Multiscale HPC Performance, NASMAT with Abaqus

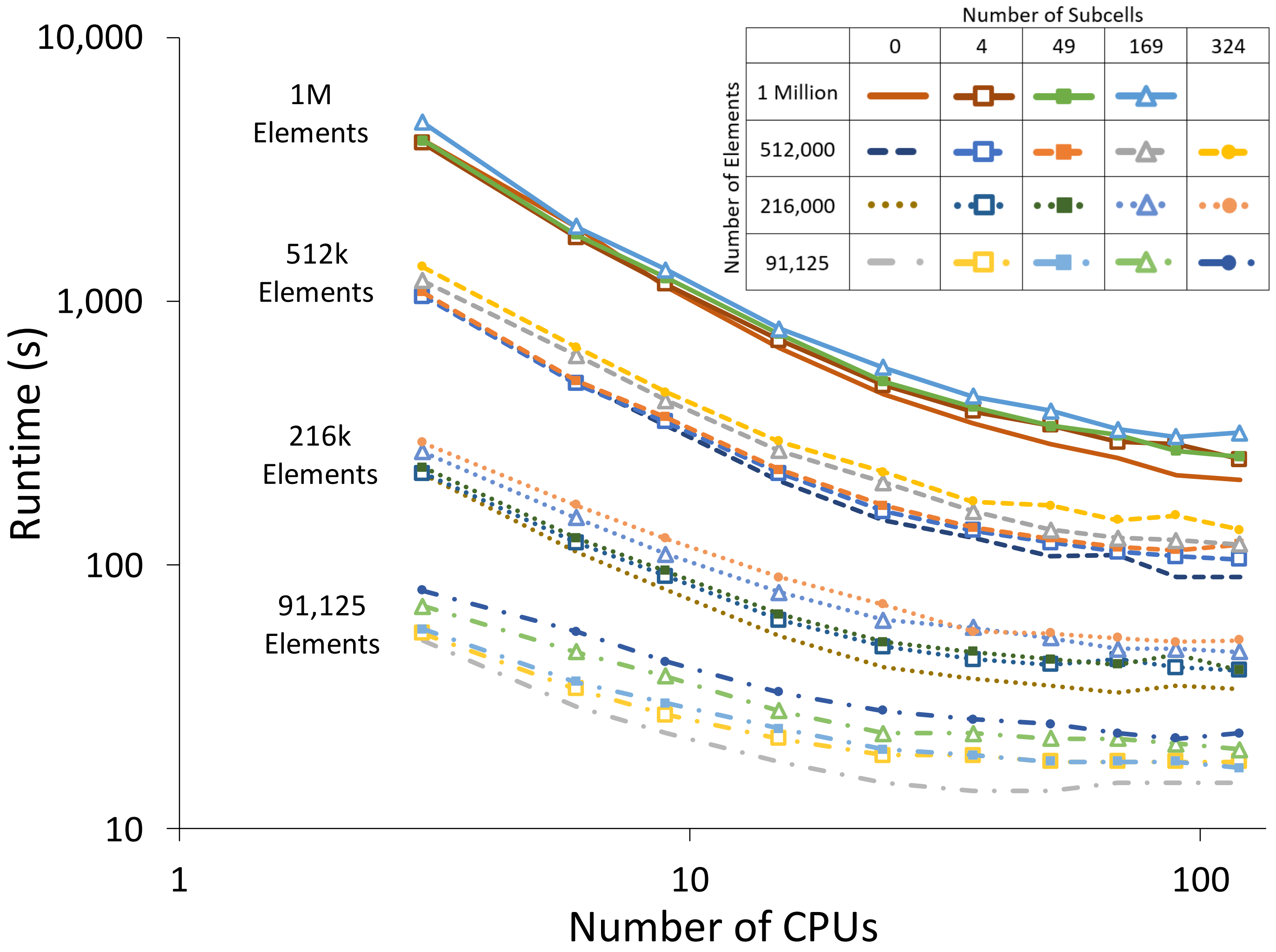
- Profiling of 4 mesh densities, each element int. pt. calling micro model (5 microscale refinements)

Structural Abaqus Model



Micromechanics Model

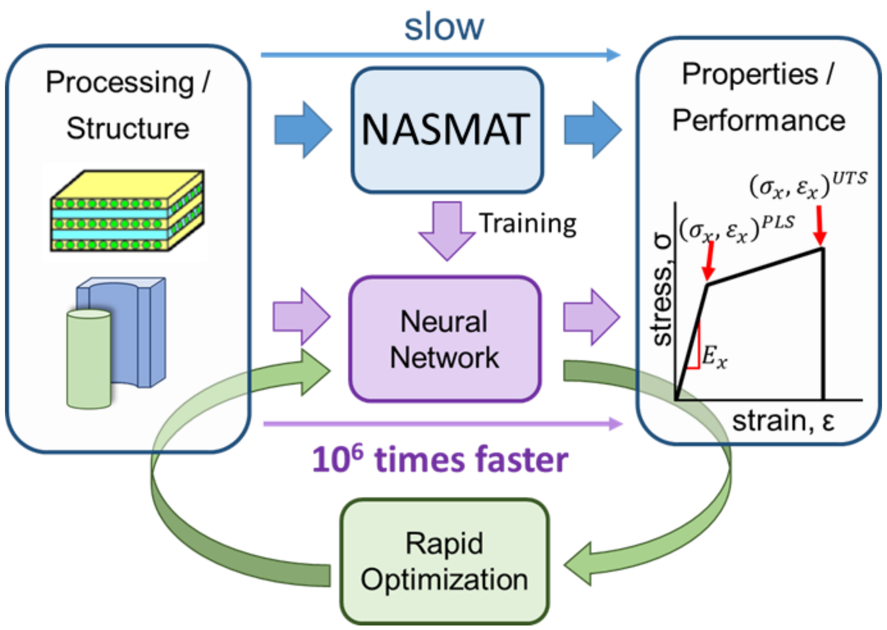


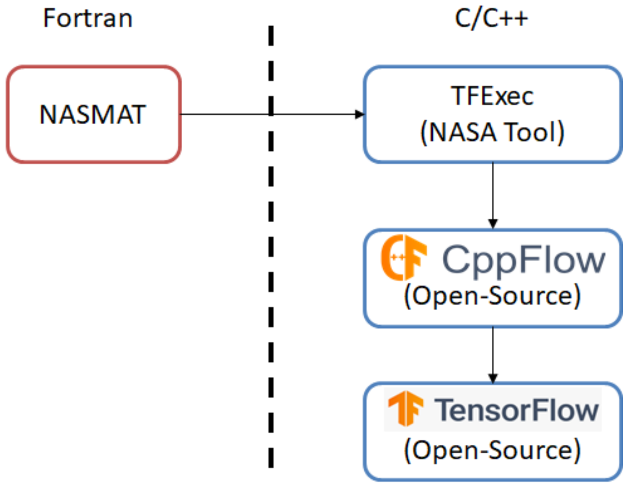


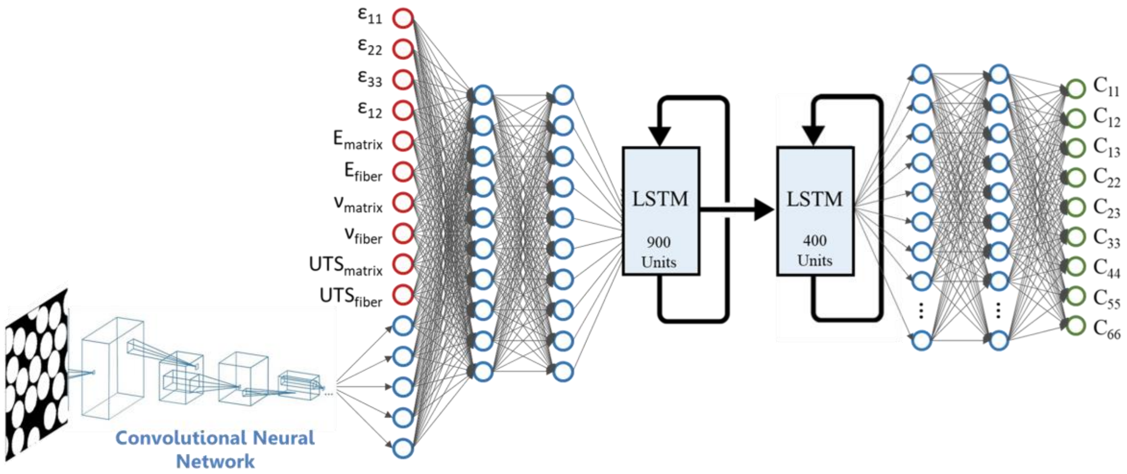
- Strong performance dependence on FEM density
- Weak dependence on micromechanics model refinement

Integration of Machine Learning (ML) Surrogates

- Neural networks shown to efficiently approximate expensive computational simulations
- Critical for aggressively exploring a material's design space
- Fast interface required due to high volume of calls from the macroscopic simulator
- NASMAT coupled to Tensorflow using TTT-developed tool, TFExec
- Full implementation into NASMAT ongoing
- TFExec able to be coupled to other Fortran-based tools
- Planned simulation of **CE5 test**



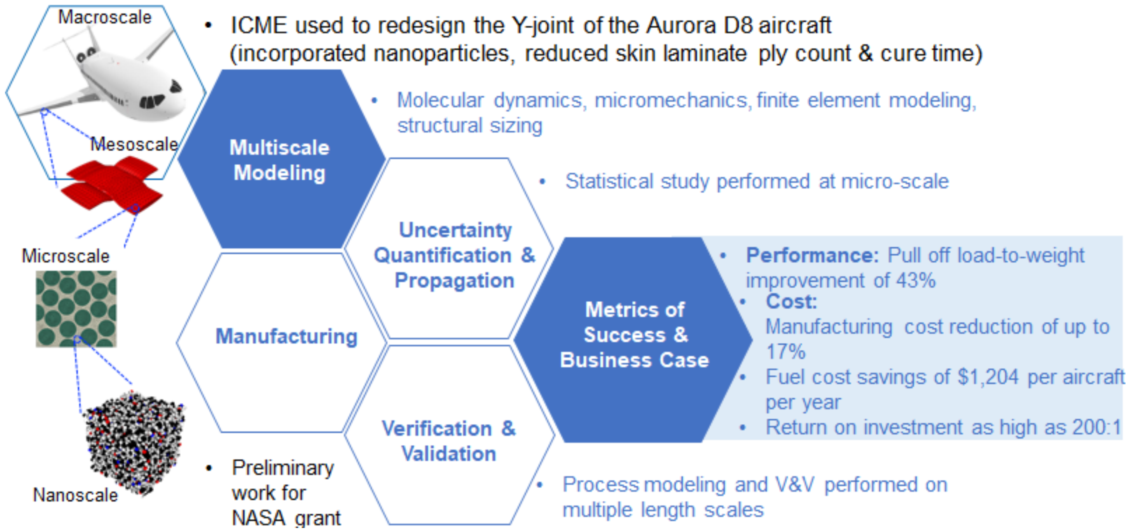




Complimentary TTT/Vision 2040 NRAs

ICME Optimization of Advanced Composite Components of the Aurora D8 Aircraft

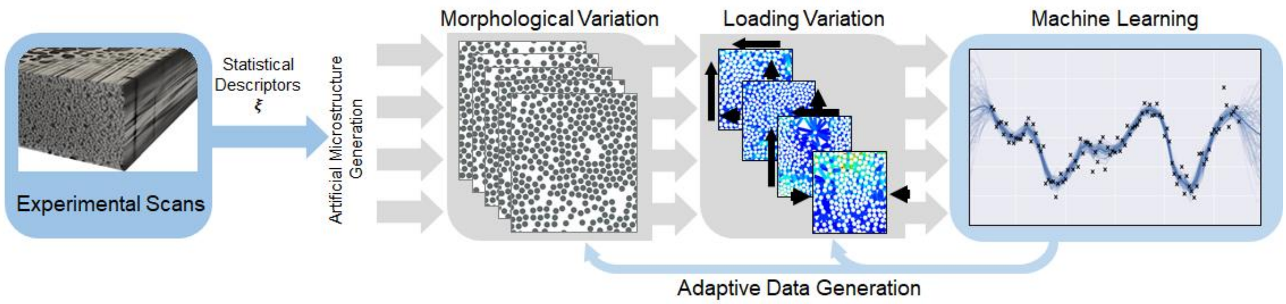
PI: Marianna Maiaru, U. Mass. Lowell; Co-PI: Greg Odegard, Mich. Tech



Multi-Scale Models based on Machine Learning and a Fiber Network Model

PI: Scott E. Stapleton, Co-PI: Farhad Pourkamali Anaraki, U. Mass. Lowell

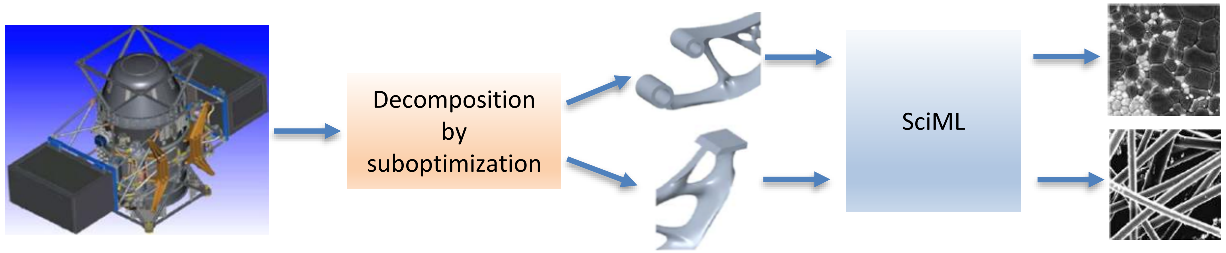
- Create efficient, reduced-order composite micro-model for generate vast amounts of ML training data
- Use Machine Learning (ML) to create a probabilistic, path-dependent surrogate model for multi-scale simulations of composite materials



Ultra Efficient Multiscale Top-Down Optimization Crossing Continuum to Micromechanics for Nonlinear High-Temperature Applications

PI: Alicia Kim, University of California, San Diego
Co PI: Karen Wilcox, University of Texas, Austin

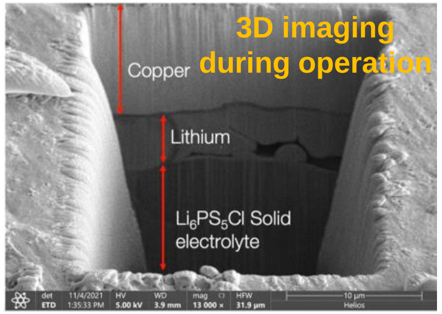
- Develop/demonstrate ultra-efficient, multiscale, physics-based and data-driven modeling/optimization capability linking microscale effects to continuum scale
- Account for/manage uncertainties
- Metallic and composite materials, high-temp path-dependence/nonlinearity

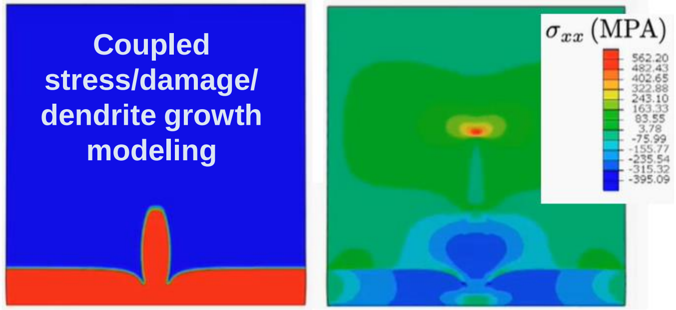


Coupling Models and *Operando* Experiments to Describe Evolution and Degradation of Solid-State Batteries

PI: Matthew McDowell; Co PIs: Claudio Di Leo, Tom Fuller; Georgia Tech

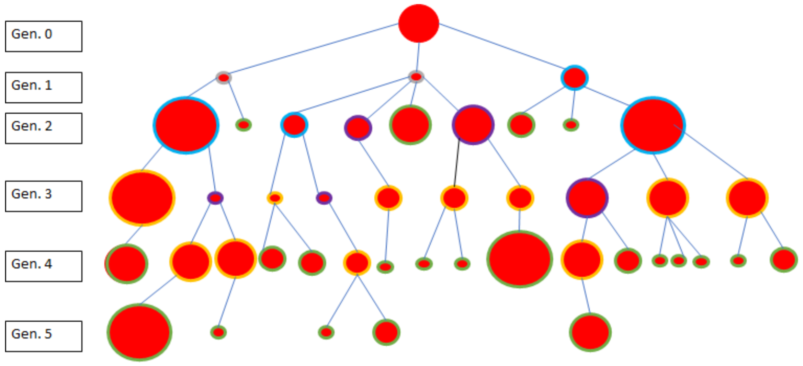
- *Operando* x-ray tomography of electro-chemo-mechanical evolution in solid-state batteries to identify/visualize mechanisms, particularly at interfaces
- Develop/validate electro-chemo-mechanical models to capture ion motion, electrochemical reactions/transport, interface evolution, and damage during charge/discharge

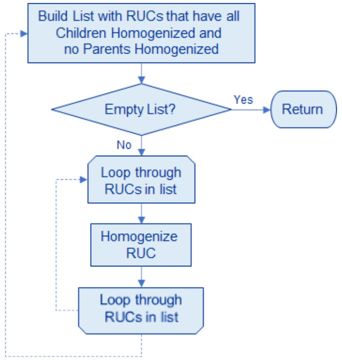




Future of NASMAT

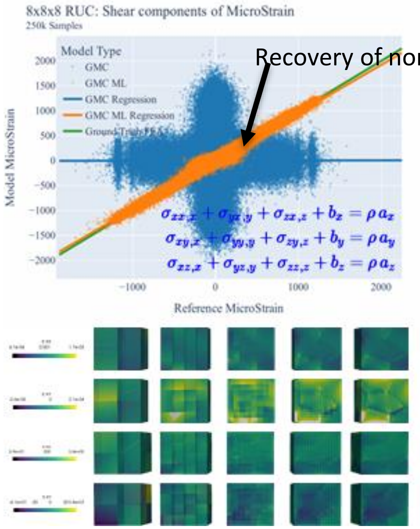
Task-based Parallelization

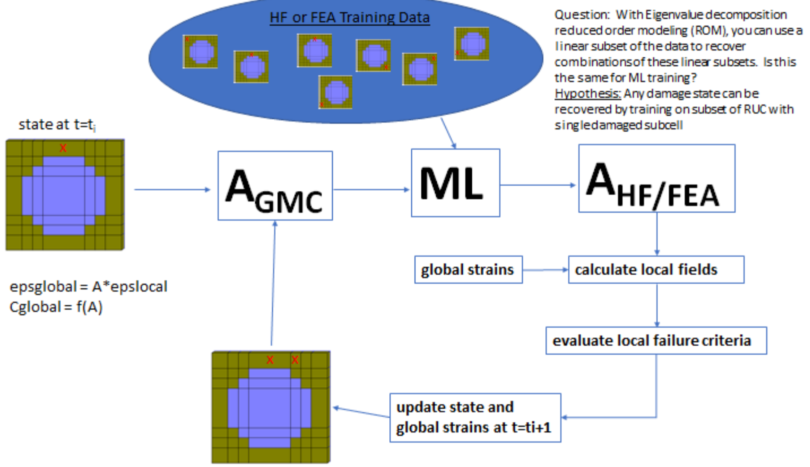




- Each red dot represents an operation
  - In the case of NASMAT this is a homogenization
- The size of the dot represents computational cost and memory requirement of the operation
  - This example demonstrates random distribution of computational load
  - Other examples could include
    - Heavy computational loading in particular generations (e.g., top heavy, bottom heavt)
- Parents are connected to children at the next Generation with a blue line
  - Parents can have multiple children
  - Each child can only have one parent
  - Parent operations cannot be performed until ALL its children operations have been completed

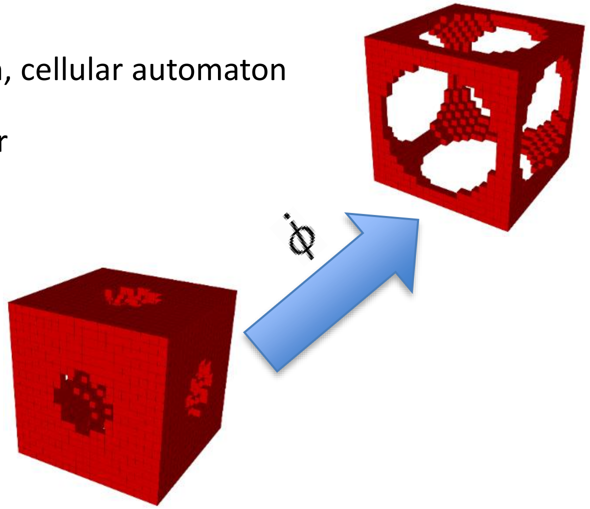
Enhancement of Micromechanics Solution Using ML for Nonlinear Solutions – Collaboration with WMU (Gustafson)



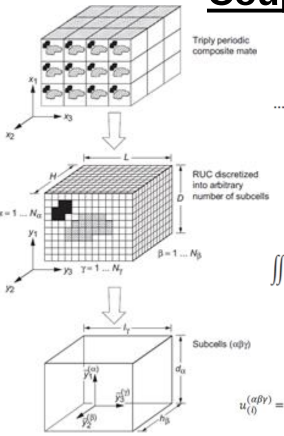


Evolving, State Variable Dependent Microstructures

- Microstructure evolution
  – Volume fraction growth/reduction, cellular automaton
- State variables:
  – Time, temperature, damage, other
- Potential applications:
  – Thermoplastics process modeling
    - Spherulite growth
  – Surface/volume recession
    – Thermal ablation, oxidation
  – Surface/volume growth
    – Grain growth, void growth



Coupled Multi-physics



$$e_a^{(\alpha\beta\gamma)}\ddot{u}^{(\alpha\beta\gamma)} + d_a^{(\alpha\beta\gamma)}\dot{u}^{(\alpha\beta\gamma)} \ldots$$

$$\ldots - \nabla\cdot\left(c^{(\alpha\beta\gamma)}\nabla u^{(\alpha\beta\gamma)} + \alpha^{(\alpha\beta\gamma)}u^{(\alpha\beta\gamma)} - \gamma^{(\alpha\beta\gamma)}\right)\ldots$$

$$\ldots + \beta^{(\alpha\beta\gamma)}\cdot\nabla u^{(\alpha\beta\gamma)} + a u^{(\alpha\beta\gamma)} = f^{(\alpha\beta\gamma)}$$

$$\iint((hu - r)dA)^{(\alpha\beta\gamma)} = \iint(hu\,dA)^{(\alpha\beta\gamma)}$$

$$\iint((\mathbf{n}\cdot(c\nabla u + \alpha u - \gamma) + qu - g + h^T\mu)dA)^{(\alpha\beta\gamma)} = \cdots$$

$$\ldots = \iint((\mathbf{n}\cdot(c\nabla u + \alpha u - \gamma) + qu)dA)^{(\alpha\beta\gamma)}$$

$$u_{(i)}^{(\alpha\beta\gamma)} = \bar{u}_{(i)}^0 + U_{(i)(000)}^{(\alpha\beta\gamma)} + \bar{y}_1^{(\alpha)}U_{(i)(100)}^{(\alpha\beta\gamma)} + \bar{y}_2^{(\beta)}U_{(i)(010)}^{(\alpha\beta\gamma)} + \bar{y}_3^{(\gamma)}U_{(i)(001)}^{(\alpha\beta\gamma)}$$

$$u_{(i)}^{(\alpha\beta\gamma)} = \bar{u}_{(i)}^0 + U_{(i)(000)}^{(\alpha\beta\gamma)} + \bar{y}_1^{(\alpha)}U_{(i)(100)}^{(\alpha\beta\gamma)} + \bar{y}_2^{(\beta)}U_{(i)(010)}^{(\alpha\beta\gamma)} + \bar{y}_3^{(\gamma)}U_{(i)(001)}^{(\alpha\beta\gamma)} + \cdots$$

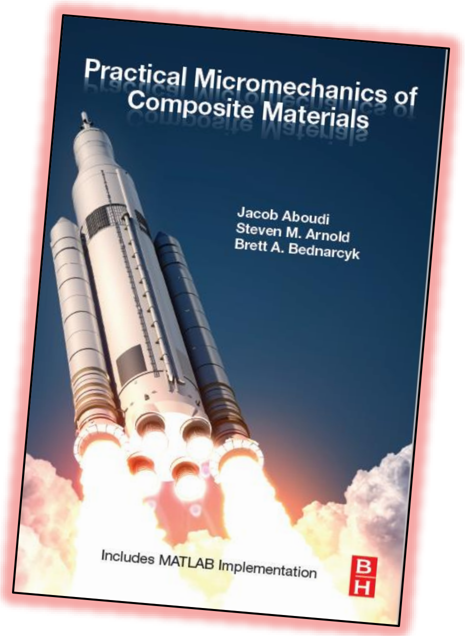
$$\ldots + \frac{1}{2}\left(3\bar{y}_1^{(\alpha)2} - \frac{d_\alpha^2}{4}\right)U_{(i)(200)}^{(\alpha\beta\gamma)} + \frac{1}{2}\left(3\bar{y}_2^{(\beta)2} - \frac{h_\beta^2}{4}\right)U_{(i)(020)}^{(\alpha\beta\gamma)} + \frac{1}{2}\left(3\bar{y}_1^{(\alpha)2} - \frac{l_\gamma^2}{4}\right)U_{(i)(002)}^{(\alpha\beta\gamma)}$$

- Postdoc project – Christopher Sorini
- Extended thermomechanical formulation of HF/GMC to accommodate general arbitrary physics
  – Dependent on type of PDE:
    - Elliptic, Parabolic, Hyperbolic
- Develop coupling strategy for multiphysics
- NASA relevant applications:
  – Batteries, oxidation, thermal ablation, acoustics

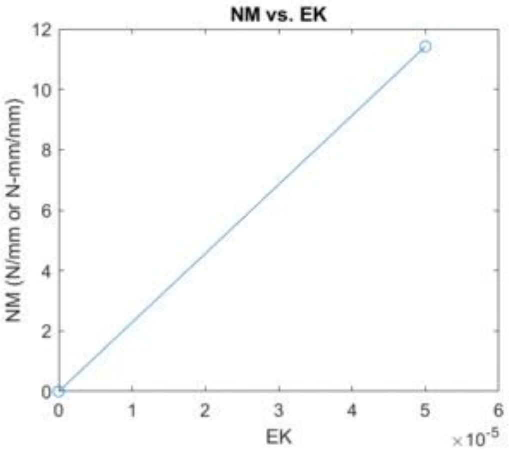
Deformation	Deformation induced heat production	Deformation controlled diffusion	Deformation induced chemical reactions	Deformation induced electromagnetism
Thermal expansion/contaction, thermal softening	**Heat Transfer**	Temperature controlled diffusion	Temperature induced chemical reactions	Temperature induced electromagnetism
Clustering	Diffusion concentration dependent heat transfer	**Diffusion**	Chemical/reactant transport	Diffusion induced electromagnetism
Reaction product accumulation	Heating associated with chemical reactions	Reaction product transport	**Chemical reactions**	Chemical reaction induced electromagnetism
Deformation due to Lorentz force, piezoelectricity, and piezomagnetism	Ohmic/Joule heating	Charged particle transport	Electromagnetic field controlled chemical reactions	**Electromagnetism**

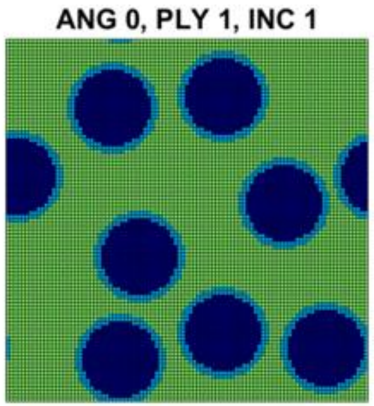
Practical Micromechanics of Composite Materials Course Textbook

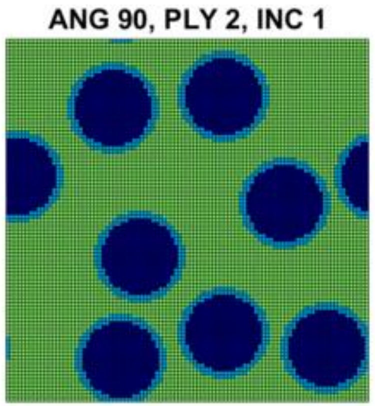
- New Elsevier textbook by J. Aboudi, S.M. Arnold, B.A. Bednarcyk (Aug. 2021)
- Intended as advanced undergrad or grad course
- Includes extensive MATLAB code to solve micromechanics and laminate problems
  - https://github.com/nasa/Practical-Micromechanics -- Open source available
- Included micromechanics theories: Voigt, Reuss, Mori-Tanaka, Method of Cells, Generalized Method of Cells (GMC), and High-Fidelity Method of Cells (HFGMC)
- All can run from within laminate plies as well
- Exercises emphasize solving real micromechanics problems
- Effective allowables for composites and laminates (initiation)
- Progressive damage (progression to final failure)
- Short course will be taught first at NASA, available outside



Example Problem from Book:
Cross-Ply CMC Laminate Progressive Damage Simulation







Questions

Relevant Publications (2020 – present)

- Book:
  - J. Aboudi, S.M. Arnold, B.A. Bednarcyk (2021). *Practical Micromechanics of Composite Materials Course Textbook,* Elsevier
- Journal Papers:
  - Pineda, E. J., Bednarcyk, B. A., Ricks, T. M., Henson, G. (2021). Efficient multiscale recursive micromechanics of composites for engineering applications. *International Journal for Multiscale Computational Engineering*, 19(4), 77-105.
  - Pineda, E. J., Bednarcyk, B. A., Ricks, T. M., Farrokh, B., Jackson, W. C. (2022). Multiscale failure analysis of a 3D woven composite containing manufacturing induced anomalies. *Composites Part A: Applied Science and Manufacturing*, 106844.
- Conference Papers:
  - Pineda, E. J., Ricks, T. M., Bednarcyk, B. A., Arnold, S. M. (2020). Software architecture and hierarchy of the NASA Multiscale Analysis Tool. *2020 Conference on Advancing Analysis & Simulation in Engineering (CAASE20)*, 16-18 June 2020, Virtual Conference.
  - Ricks, T. M., Pineda, E. J., Bednarcyk, B. A., Arnold, S. M. (2020). Application of the NASA Multiscale Analysis Tool: Multiscale integration and interoperability. *2020 Conference on Advancing Analysis & Simulation in Engineering (CAASE20)*, 16-18 June 2020, Virtual Conference.
  - Pineda, E. J., Bednarcyk, B. A., Ricks, T. M., Farrokh, B., Jackson, W. C. (2020). Multiscale failure analysis of a 3D woven unit cell containing defects. *American Society for Composites 35th Technical Conference*, 14-17 September 2020, Virtual Conference.

Relevant Publications (2020 – present)

- Conference Papers:
  - Pineda, E. J., Ricks, T. M., Bednarcyk, B. A., Arnold, S. M. (2021). Benchmarking and performance of the NASA Multiscale Analysis Tool. *AIAA SciTech 2021 Forum*, 11-15 & 19-21 January 2021, Virtual Conference.
  - Pineda, E. J., Silva, L. F., Gustafson, P. A. (2021). Geometric requirements for modeling polycrystalline representative volume element using the generalized method of cells. *AIAA SciTech 2021 Forum*, 11-15 & 19-21 January 2021, Virtual Conference.
  - Ricks, T. M., Pineda, E. J., Bednarcyk, B. A., Arnold, S. M. (2021). Progressive failure analysis of 3D woven composites via multiscale recursive micromechanics. *AIAA SciTech 2021 Forum*, 11-15 & 19-21 January 2021, Virtual Conference.
  - Silva, L. F., Pineda, E. J., Gustafson, P. A. (2021). Geometric sensitivity of residual fields in metal additive manufacturing. *AIAA SciTech 2021 Forum*, 11-15 & 19-21 January 2021, Virtual Conference.
  - Silva, L. F., Pineda, E. J., Gustafson, P. A. (2021). Porosity model parameter effects on metal additive manufacturing simulations. *AIAA SciTech 2021 Forum*, 11-15 & 19-21 January 2021, Virtual Conference.
  - Sorini, A. J., Pineda, E. J., Stuckner, J., Gustafson, P. A. (2021). A convolutional neural network for multiscale modeling of composite materials. *AIAA SciTech 2021 Forum*, 11-15 & 19-21 January 2021, Virtual Conference.
  - Bukenya, K., Olaya, M., Pineda, E. J., Maiarù, M. (2021). Effect of boundary conditions on process-induced stresses in a plain weave unit cell. *American Society for Composites 36th Technical Conference*, 20-22 September 2021, Virtual Conference.
  - Bednarcyk, B. A., Pineda, E. J., Ricks, T. M., Mital, S. K. (2021). Progressive damage response of 3D woven composites via the multiscale recursive micromechanics solution with tailored fidelity. *American Society for Composites 36th Technical Conference*, 20-22 September 2021, Virtual Conference.

Relevant Publications (2020 – present)

- Conference Papers:
  - Bednarcyk, B. A., Ricks, T. M., Pineda, E. J., Murthy, P. L. N., Mital, S. K., Hu, Z., Gustafson, P. A. (2022). Thermal conductivity of 3D woven composite thermal protection system materials via multiscale recursive micromechanics. *2022 AIAA SciTech Forum*, 3-7 January 2022, San Diego, CA.
  - Bukenya, K., Olaya, M., Pineda, E. J., Maiarù, M. (2022). Process modeling of woven textiles. *2022 AIAA SciTech Forum*, 3-7 January 2022, San Diego, CA.
  - Plaka, E., Jones, S. P., Bednarcyk, B. A., Pineda, E. J., Li, R., Maiarù, M. (2022). Application of rapid design tool to a 3D woven structural joint. *2022 AIAA SciTech Forum*, 3-7 January 2022, San Diego, CA.
  - Gustafson, P. A., Pineda, E. J., Ricks, T. M., Bednarcyk, B. A., Hearley, B. L., Stuckner, J. (2022). A convolutional neural network for enhancement of multi-scale localization in granular metallic representative unit cells. *2022 AIAA SciTech Forum*, 3-7 January 2022, San Diego, CA.

Relevant Publications (2020 – present)

- NASA/TMs:
  - Silva, L. F., Yapor, F., Pineda, E. J., Gustafson, P. A. (2020). Effect of material porosity on residual stress in an additive manufacturing simulation using generalized method of cells. *NASA/TM-20205000292*.
  - Husseini, J. F., Stapleton, S. E., Pineda, E. J. (2020). An algorithm for characterization of fiber aggregation in composite microstructures. *NASA/TM-20205006994*.
  - Hearley, B. L., Pineda, E. J., Bednarcyk, B. A., Murman, S. M., Pankow, M. (2020). Micromechanics modeling of textiles for re-entry parachute applications. *NASA/TM-20205011621*.
  - Bukenya, K., Olaya, M., Shah, S., Pineda, E. J., Ricks, T. M., Maiarù, M. (2021). Residual stresses induced due to curing of bulk matrix in a simplified three-dimensional (3D) woven repeating unit cell. *NASA/TM-20205009287*.
  - Hearley, B., Stuckner, J., Pineda, E. J., Murman, S. (2022). Predicting unreinforced fabric mechanical behavior with recurrent neural networks. *NASA/TM-20210023708*.

Backup